Performance of Horizontal Infrastructure in Christchurch City through the 2010-2011 Canterbury Earthquake Sequence

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Summary

This is an interim report from the research study performed within the NHRP Research Project "Impacts of soil liquefaction on land, buildings and buried pipe networks: geotechnical evaluation and design, Project 3: Seismic assessment and design of pipe networks in liquefiable soils". The work presented herein is a continuation of the comprehensive study on the impacts of Christchurch earthquakes on the buried pipe networks presented in Cubrinovski et al. (2011).

This report summarises the performance of Christchurch City's potable water, waste water and road networks through the 2010-2011 Canterbury Earthquake Sequence (CES), and particularly focuses on the potable water network. It combines evidence based on comprehensive and well-documented data on the damage to the water network, detailed observations and interpretation of liquefaction-induced land damage, records and interpretations of ground motion characteristics induced by the Canterbury earthquakes, for a network analysis and pipeline performance evaluation using a GIS platform.

The study addresses a range of issues relevant in the assessment of buried networks in areas affected by strong earthquakes and soil liquefaction. It discusses performance of different pipe materials (modern flexible pipelines and older brittle pipelines) including effects of pipe diameters, fittings and pipeline components/details, trench backfill characteristics, and severity of liquefaction. Detailed breakdown of key factors contributing to the damage to buried pipes is given with reference to the above and other relevant parameters.

Particular attention is given to the interpretation, analysis and modelling of liquefaction effects on the damage and performance of the buried pipe networks. Clear link between liquefaction severity and damage rate for the pipeline has been observed with an increasing damage rate seen with increasing liquefaction severity. The approach taken here was to correlate the pipeline damage to *LRI* (Liquefaction Resistance Index, newly developed parameter in Cubrinovski et al., 2011) which represents a direct measure for the soil resistance to liquefaction while accounting for the seismic demand through PGA. Key quality of the adopted approach is that it provides a general methodology that in conjunction with conventional methods for liquefaction evaluation can be applied elsewhere in New Zealand and internationally.

Preliminary correlations between pipeline damage (breaks km^{-1}), liquefaction resistance (*LRI*) and seismic demand (*PGA*) have been developed for AC pipes, as an example. Such correlations can be directly used in the design and assessment of pipes in seismic areas both in liquefiable and non-liquefiable areas.

Preliminary findings on the key factors for the damage to the potable water pipe network and established empirical correlations are presented including an overview of the damage to the waste water and road networks but with substantially less detail. A comprehensive summary of the damage data on the buried pipelines is given in a series of appendices.

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List of Acronyms

AC	Asbestos Cement
CBD	Central Business District
CCC	Christchurch City Council
CCL	City Care Limited
CCTV	Closed-Circuit Television
CERA	Canterbury Earthquake Recovery Authority
CES	Canterbury Earthquake Sequence
CI	Cast Iron
CLS	Concrete-Lined Steel
CONC	Concrete
DI	Ductile Iron
EW	Earthenware
FH	Fulton Hogan
GI	Galvanised Iron
GIS	Geographic Information System(s)
GPS	Global Positioning System
HDPE	High-Density Polyethylene
LRI	Liquefaction Resistance Index
MDPE80	Medium-Density Polyethylene 80
MPVC	Modified Polyvinyl Chloride
PDA Tool	Pipe Damage Assessment Tool
PVC	Polyvinyl Chloride
RCRR	Reinforced Concrete Rubber-Ring jointed
S	Steel
SCIRT	Stronger Christchurch Infrastructure Rebuild Team
UC	University of Canterbury

1.0 Introduction

This is an interim report from the research study performed within the NHRP Project "Impacts of soil liquefaction on land, buildings and buried pipe networks: geotechnical evaluation and design, Project 3: Seismic assessment and design of pipe networks in liquefiable soils". The work presented herein is a continuation of the comprehensive study on the impacts of Christchurch earthquakes on the buried pipe networks reported in Cubrinovski et al. (2011).

This report summarises the performance of Christchurch City's potable water, waste water and road networks through the 2010-2011 Canterbury Earthquake Sequence (CES). The lessons from this work have important implications for the resilience of critical urban infrastructure and its management in seismically vulnerable areas. This report particularly focuses on the potable water network, and also provides an overview of the nature of the potable water data used with an emphasis on the historical development and quality of infrastructure spatial databases.

Prior to the CES, the Christchurch City Council (CCC) had a detailed and comprehensive geospatial database of most components of the potable water system, and with the commencement of the CES the Stronger Christchurch Infrastructure Rebuild Team (SCIRT) developed an award-winning Geographic Information System (GIS) for managing the voluminous infrastructure data required for understanding earthquake impacts and managing the rebuild. As a result, the CES has generated one of the most comprehensive databases in the world for understanding the seismic impacts on an urban environment. The extended time period over which events in the CES have occurred has provided insight into the performance and resilience of the potable water system through multiple seismic events, the quantification of which will be valuable for informing seismic risk assessment methodologies.

Also presented here are initial analyses of the performance of Christchurch City's waste water network. Unlike the potable water system that is pressurised and relatively shallow (less than 1 m depth), the majority of the waste water network is comprised of gravity pipes typically placed at 2.0 m to 3.5 m depth. Therefore, in contrast to the potable water system where faults were readily apparent and able to be linked to specific earthquake events, the waste water system repairs are occurring over a much longer timeframe and event-specific damage is difficult to determine. Despite this, analysis presented here demonstrates major patterns of pipe performance, along with more detailed characterisation of waste water manhole behaviour in response to liquefaction. We also present initial analysis of performance of Christchurch City's road network, particularly in response to the Christchurch earthquake of 22 February 2011.

2.0 The Canterbury Earthquake Sequence

Between September 2010 and December 2011, Christchurch, the second largest city of New Zealand (population: ~ 350,000; area: ~ 450 km2), was hit by a sequence of strong earthquakes including six significant events: 4 September 2010 (Moment Magnitude, M_w=7.1), 22 February 2011 (M_w=6.2), 13 June 2011 (two earthquakes: M_w=5.3 at 1 p.m. and M_w=6.0 at 2:20 p.m.) and 23 December 2011 (two earthquakes: M_w=5.8 at 1:58 p.m. and M_w=5.9 at 3:18 p.m.) earthquakes. The causative faults of all these earthquakes were very close to or within the city boundaries thus generating very strong ground motions and causing tremendous damage throughout the city. The 22 February 2011 earthquake was particularly devastating. It caused 185 fatalities, collapse of two multi-storey reinforced concrete buildings, and collapse or partial collapse of many unreinforced masonry structures including the historic Christchurch Cathedral. The Central Business District (CBD) of Christchurch, which was the heart of the city just east of Hagley Park, was practically lost with majority of its 3,000 buildings being damaged beyond repair. Widespread liquefaction in the suburbs of Christchurch, as well as rock falls and slope/cliff instabilities in the Port Hills affected tens of thousands of residential buildings and properties, and shattered the lifelines and infrastructure over approximately one third of the city area. The total economic loss caused by the 2010-2011 Christchurch earthquakes is estimated to be at ~30 billion NZ dollars (or 15% of New Zealand's GDP), and the cost of the rebuild at ~40 billion NZ dollars.

Causative fault planes and largest moment magnitude (M_w) earthquake epicentres for the 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011 events are shown in Figure 1. The CES commenced on 4 September 2010, and there has been an eastward migration of activation of the causative faults subsequent to the September 2010 event, with the February, June and December earthquakes occurring within 4-10 km of the Christchurch CBD. As of 29 June 2013 there were on-going ~3.0 magnitude aftershocks still occasionally being felt in Christchurch City (GeoNet, 2013; http://www.geonet.org.nz/quakes/region/newzealand/2013p484195).

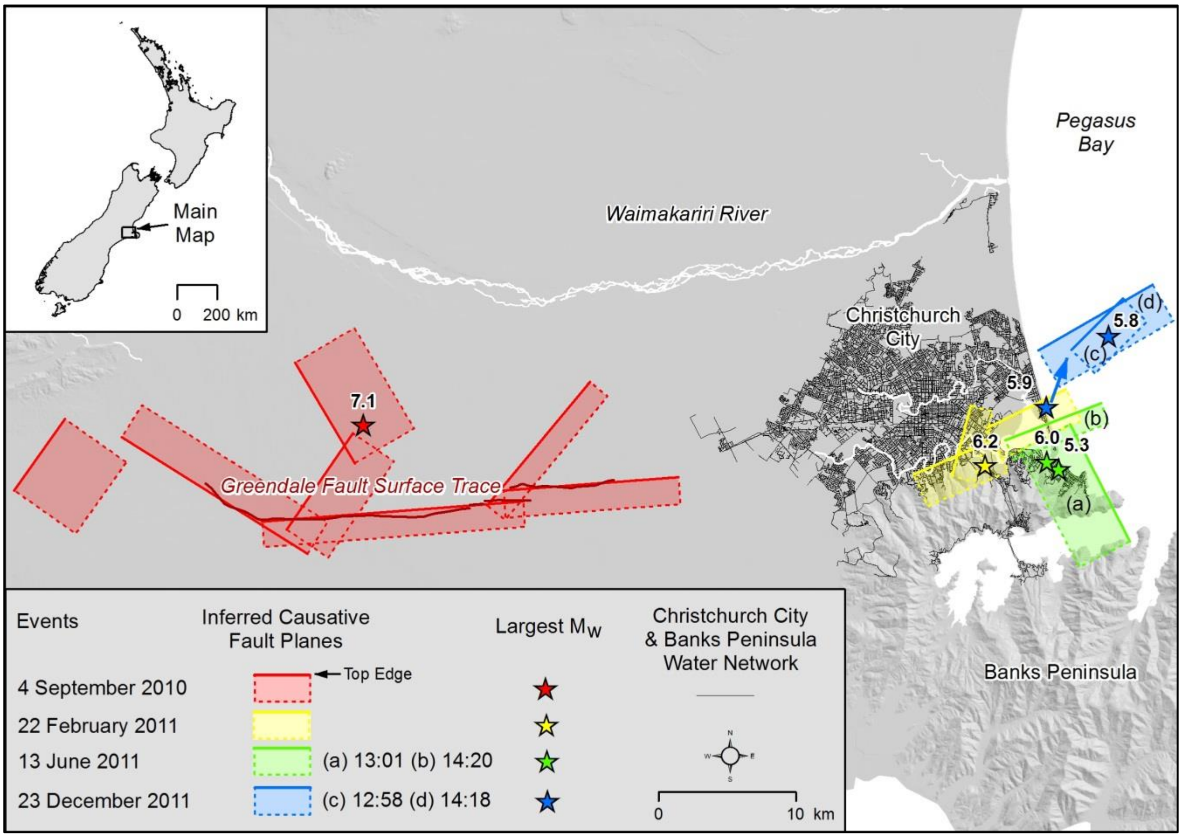


Figure 1. Locations of Canterbury Earthquake Sequence causative fault planes. Largest Moment Magnitudes (M_w) for the four major events and Greendale Fault surface trace (4 September 2010) are also shown. The fault plane for the 23 December 2011 M_w 5.9 event is indicated with a blue arrow. Also shown is the water supply network for Christchurch City and Banks Peninsula.

3.0 Potable Water System

3.1 Introduction

Initial research (Cubrinovski et al., 2011a; 2013) on the performance of Christchurch's potable water supply through the CES has shown that the network has been subjected to very large, and highly non-uniform, ground deformation and seismic loads which were often above the available network capacity to sustain such movements and loads, leading to widespread damage and failure/breaks. There was a clear link between liquefaction severity and pipe network damage, with nearly 80% of the damaged water mains being in liquefied areas. Ductile materials and flexible pipe systems such as Polyvinyl Chloride (PVC) and Polyethylene (PE) pipes performed very well, with several times less damage than other pipe materials such as Asbestos Cement (AC), Steel (S), and Galvanised Iron (GI). Despite the large number of system breaks, potable water service was restored quickly after each major CES event, and after 50 days a post-quake steady state of 2-3 repairs a day was reached, about four times the average of pre-quake repairs. In the wake of the quakes, the Christchurch City Council (CCC) has developed provisional performance objectives for the system based on their technical and operational scrutiny of system performance and community service expectations (Henderson, 2011), the achieving of which is aimed to provide timely service restoration after future potential events.

While this work has elucidated the major patterns of potable water network damage and is important for understanding system resilience and vulnerabilities, there remains the need for detailed understanding of pipe system failures from a mechanics viewpoint. We have noted previously that our initial research focused on classes of pipe material alone, and pipe failures were not differentiated into failures of pipe fittings and other components, and failures of the pipe itself (Cubrinovksi et al., 2011a, 2013). Such details may more fully inform the criteria currently applied to decisions around replacing lengths of pipe in the recovery/rebuild of Christchurch (CCC, 2011), and will provide more comprehensive understanding of what failures may be expected in future events in Canterbury, around New Zealand and in cities across the world whose water system pipe materials are similar to those of Christchurch.

Here are presented updated, more comprehensive and detailed analyses using recent improved SCIRT data sets through the CES, and pipe modes of failure as can best be determined from available data. As in our previous study (Cubrinovksi et al., 2011a) damage assessments are investigated according to pipe materials, but in this report we further address differing pipe diameters and characterise modes of failure. We also present preliminary damage analyses using conditional PGAs (Bradley and Hughes, 2012). Finally we address issues of geospatial infrastructure data management critical for both optimal business-as-usual and post-disaster asset management.

3.1.1 System characteristics and development

The Christchurch water supply system is an integrated citywide network that sources high quality groundwater from confined aquifers, and pumps the water into a distribution pipe network consisting of approximately 1700 km of watermains and 2000 km of submains (CCC 2010a). The water is supplied from approximately 150 wells at over 50 sites, 8 main storage reservoirs, 37 service reservoirs and 26 secondary pumping stations. The system is divided into distinct pressure zones and uses bulk storage reservoirs to assist in meeting peak demands and providing for emergencies. The wells and pumping stations are evenly distributed throughout the city, providing efficient delivery of water at a relatively uniform pressure within each zone. Watermains and submains are located almost exclusively within legal roads, at shallow depths (maximum depth 0.8 m). The preferred location for principal watermains is in the carriageway, about 2.0-2.5 m from the kerb. Submains are typically installed beneath footpaths approximately 150 mm from boundaries. Submains are served from crossovers which are usually located at fire hydrants. All crossovers are 50 mm in diameter regardless of the submain size, with the preferred connection into either a tapped hydrant riser or into the main at a hydrant tee. The system is designed so that turning off a maximum of five valves can isolate any area in the network that serves no more than 50 properties. A typical layout of watermains and submains is shown in Figure 2 (CCC, 2010b).

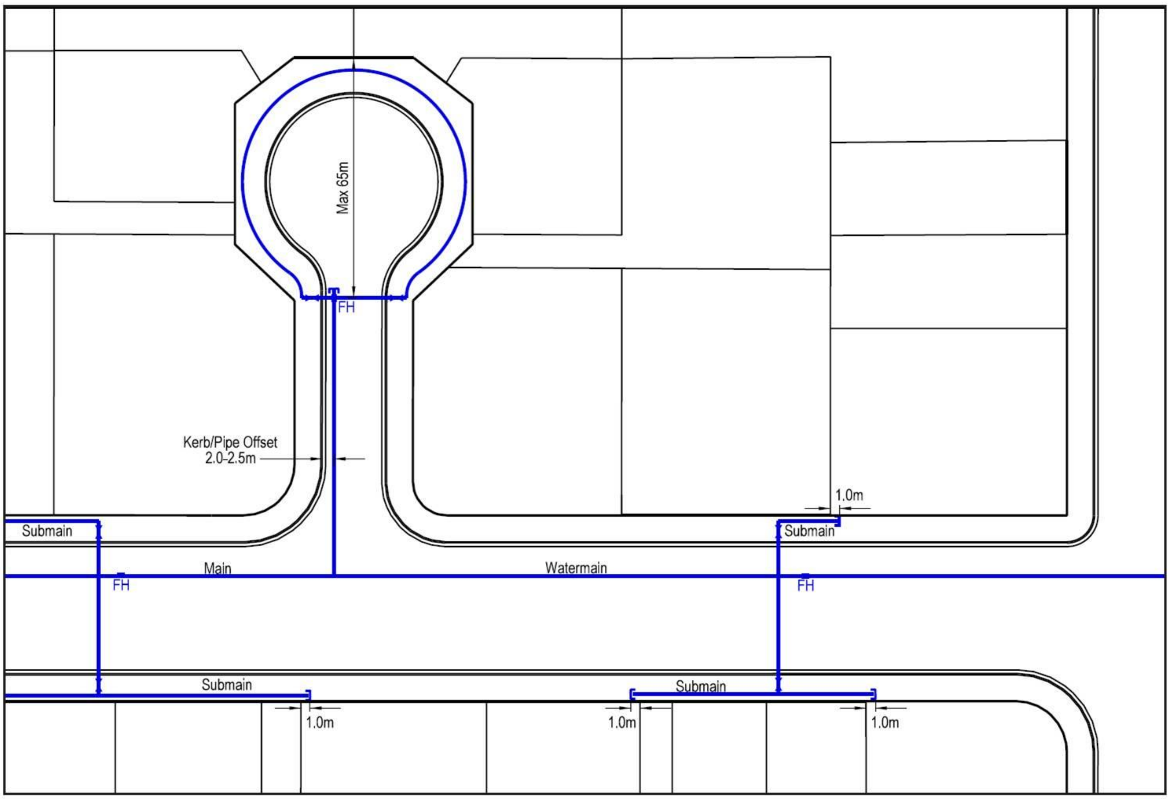


Figure 2. Example of mains and submains layout (blue lines) along a thoroughfare and cul-de-sac. FH = fire hydrant. From Christchurch City Council (2010b).

This study uses data obtained through the Christchurch City Council (CCC) and the Stronger Christchurch Infrastructure Rebuild Team (SCIRT), and its spatial extent is therefore confined to the Christchurch City urban area and Banks Peninsula District communities within Lyttelton harbour. Water networks in Selwyn and Waimakariri Districts are not considered here.

The spatial variation in pipe types across Christchurch City and Banks Peninsula reflects the historical development of the system (see Figure 3 to Figure 6). Although a comprehensive system for storm water and waste water drainage was developed in the 1870s Christchurch City did not have a fully reticulated potable water supply until the 1950s; until then individual boroughs were served by local bores visa local networks (see Clark (1878) and Wilson (1989) for historical background). From the 1890s the systems across Christchurch City and Banks Peninsula was comprised of Cast Iron (CI) and Steel (S) mains, and submains comprised of GI. From the early

1950s AC was the primary mains pipe material installed as the city experienced a significant expansion in the decade following World War 2, leading to a large fraction of the mains system to be comprised of this material (~52% as of 4 September 2010). Installation of GI submains ceased by 1980, and CI, S and AC mains stopped being installed by 1990. From 1990 trunk mains and mains were comprised of PVC, Concrete-Lined Steel (CLS) and Ductile Iron (DI) (~14%, ~5% and ~4%, respectively, of trunk mains and mains at 4 September 2010). Modified Polyvinyl Chloride (MPVC) was trialled from 2000, but its installation ceased in 2005 following reports of poor pipe performance. Submains comprised of High-Density Polyethylene (HDPE) began to be installed from 1980, and from 2000 HDPE was also used for mains. As of 4 September 2010 at the commencement of the CES, Christchurch's potable water network was comprised of a range of materials, with GI, CI and S (13% of the system length combined) having been installed for nearly a century after 1890, and AC (24% of the system length) installed over four decades. More recently installed from 1990, PVC and MPVC mains together comprised 17% of the network. From the 1980s new submains were constructed from HDPE, and from 2000 MDPE80 was used - they comprised 29% and 14%, respectively, of the network length on 4 September 2010.

The major pipe types and materials of the potable water system are summarised in Table 1 below.

Table 1. Summary of Christchurch City and Lyttelton Harbour potable water network pipe types and materials as of 4 September 2010.

Pipe Material	Trunk Mains		Mains		Submains		Crossovers		Total km	% of Total Network
	km	% of Trunk Mains	km	% of Mains	km	% of Submains	km	% of Crossovers		
HDPE	-	-	0.296	<1	845.250	56	68.951	48	914.497	27
AC	4.819	17	849.922	52	15.285	1	0.941	1	870.968	26
MDPE80	-	-	4.649	<1	412.598	27	39.981	28	457.227	14
PVC	0.282	1	314.813	19	67.594	4	3.556	2	386.244	12
CI	0.081	<1	188.520	11	0.602	<1	0.008	<1	189.210	6
GI	-	-	2.354	<1	154.049	10	29.563	21	185.965	6
MPVC	-	-	148.379	9	0.584	<1	0.030	<1	148.993	4
CLS	13.941	48	38.079	2	0.038	<1	-	-	52.058	2
DI	0.020	<1	51.830	3	0.000	<1	-	-	51.850	2
S	9.765	33	23.892	1	0.232	<1	0.011	<1	33.900	1
Other	0.285	1	27.375	2	14.367	1	0.305	<1	42.333	1
Total (% of network)	**29.193 (1)**		**1650.107 (50)**		**1510.598 (45)**		**143.345 (4)**		**3333.243**	

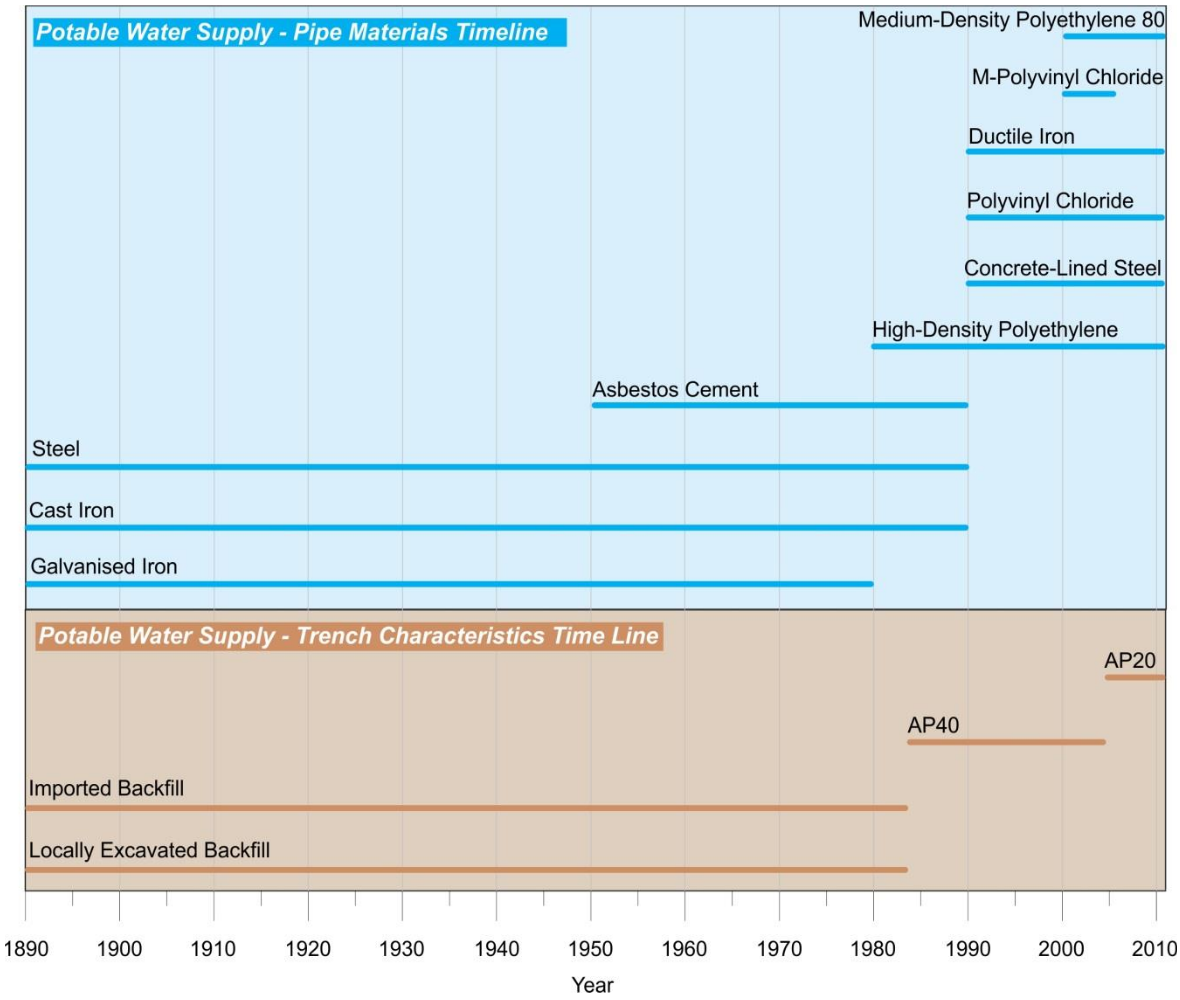


Figure 3. Decadal time lines of installation for Christchurch City and Banks Peninsula potable water supply pipe materials (1890-2012), and trench backfill characteristics.

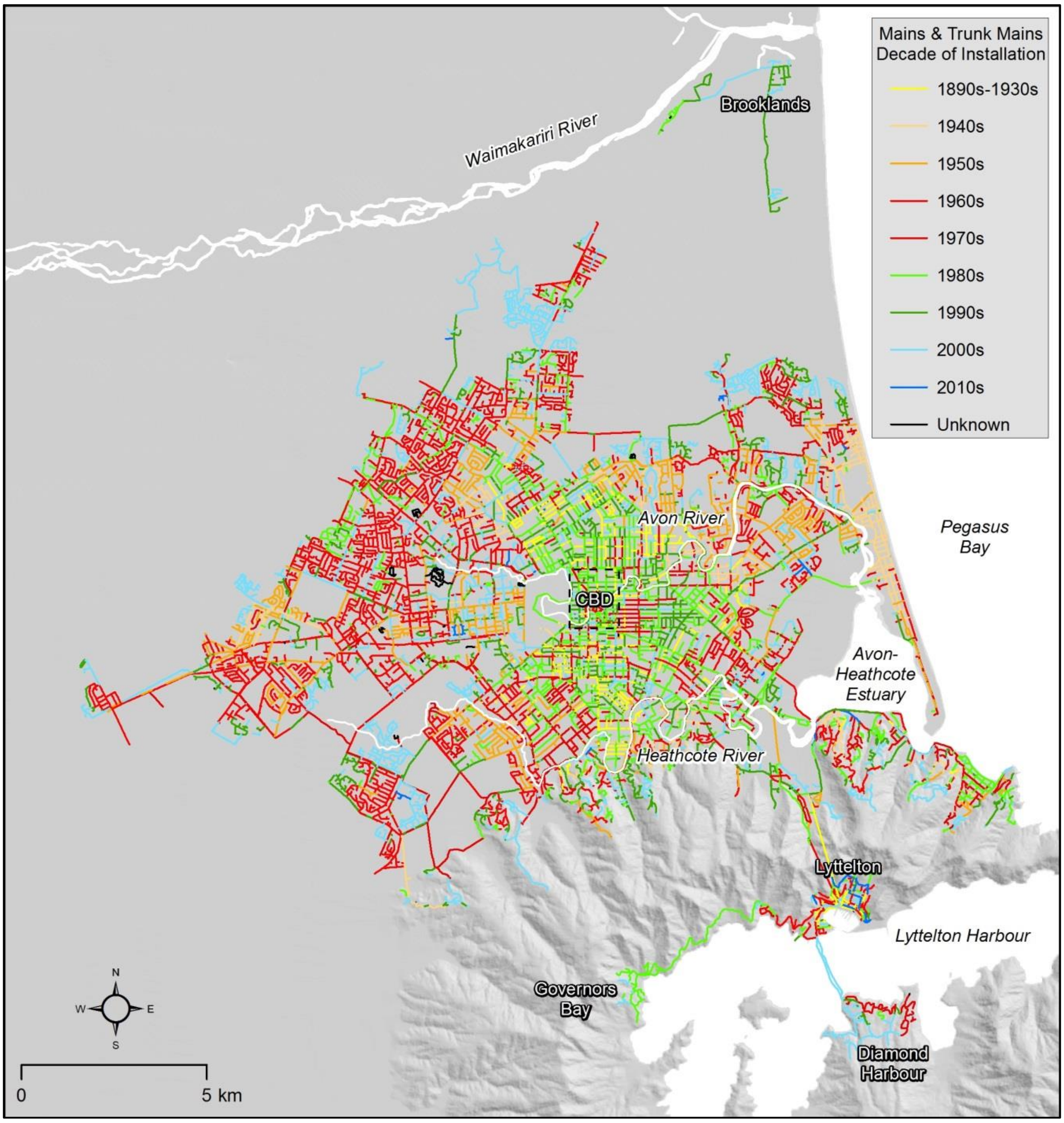


Figure 4. Christchurch City and Lyttelton Harbour potable water supply trunk mains and mains mapped according to decade of installation.

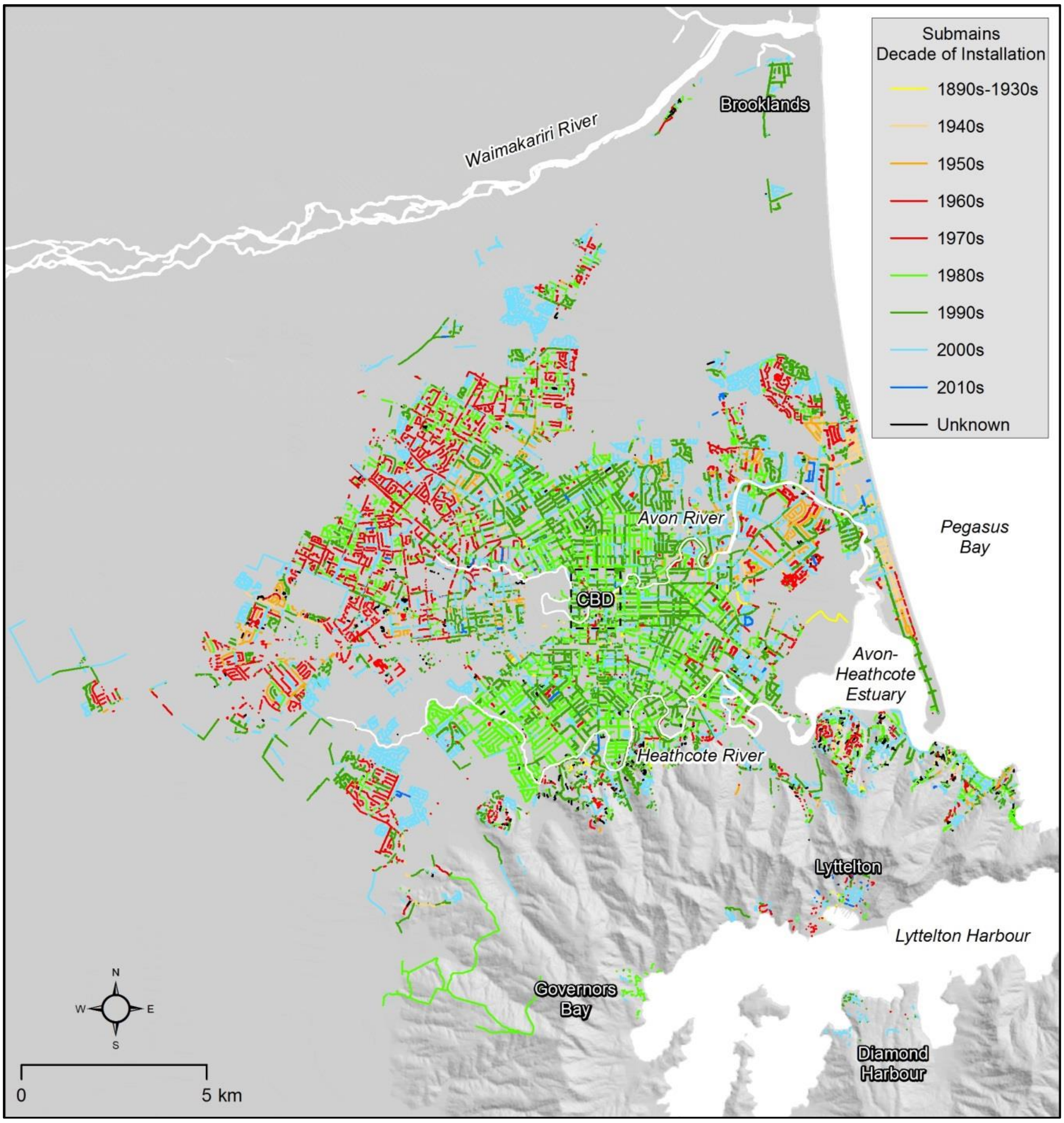


Figure 5, Christchurch City and Lyttelton Harbour potable water supply submains mapped according to decade of installation

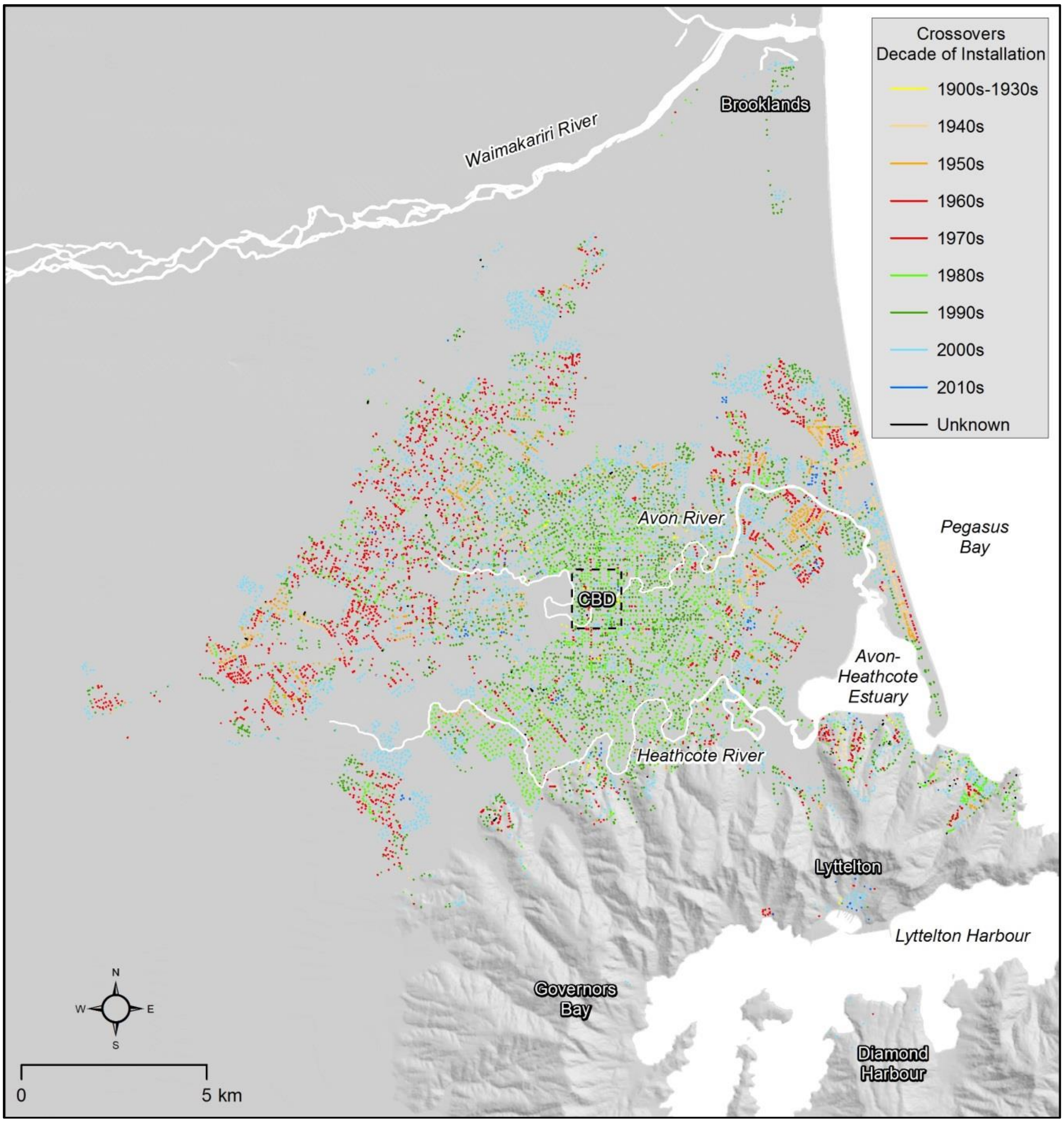


Figure 6. Christchurch City and Lyttelton Harbour potable water supply crossovers mapped according to decade of installation.

3.2 Damage Analysis

3.2.1 Data Overview

Water supply network

Our previous analyses (Cubrinovski et al., 2011; 2013) relied upon network data sourced from the CCC. The CCC water network spatial data were developed initially in the 1990s from digitised hard copy plans, and the data base has been since updated for managing the city's assets with continued suburban expansion of Christchurch City. Spatial inaccuracies and incorrect attribute data are assumed to have comprised an uncertain percentage of the data, but prior to the CES it is estimated that more than 95% of water mains records were accurate. This accuracy was high enough to have overall confidence in knowledge of the system for asset management; accuracy of the submains was considered of less importance. However, the significant and widespread damage to the system through the CES has revealed unexpected data inaccuracies in the submains records as determined by the system repairs conducted by City Care Limited (CCL). This is particularly the case with approximately 200 pipes that were mistakenly designated as High-Density Polyethylene (HDPE) in the CCC spatial data base, but were observed by the repair contractors to be mostly GI pipes, with a minority being AC. This misattribution stems from when hard-copy CCC records were updated to electronic form, and instead of pipes being ascribed to GI or AC they were labelled according to previous repairs that used small sections of HDPE material. Although these misattributions comprise only a relatively small percentage of the system, the incorrect data has proved problematic in wider assessments of pipe performance for infrastructure recovery, where criteria for determining asset repair/replacement (CCC, 2011) depend on accurate information.

Since the formation of SCIRT in August 2011, the original CCC water network spatial databases have been updated based on pipe materials observed in repairs. This has been an iterative process where discrepancies identified by SCIRT staff are clarified with CCL, and the SCIRT data base updated with best current information on pipe material and diameter. The updated network data are in turn transferred weekly to the CCC for their own asset management system. Prior to the CES, information flow from CCL to CCC was incomplete and largely anecdotal, with questionable accuracy. There appears to have been no overall drive for comprehensive and seamless data sharing between CCC and CCL to maintain accuracy, and in the pre-CES environment such issues were not pressing.

The most recent water supply network data used here were obtained from SCIRT's GIS team in March 2013, and represents the most accurate picture of the system to date. Occasional discrepancies between pipe network information and pipe types observed in repairs are still being identified.

Water network damage and repair data

Following 4 September 2010 there was little detailed systematic documentation of pipe damage and repairs, although repairs to some water mains were recorded (see Appendix D). There were cases of misidentified pipes due to the types of field data capture devices being used, as discussed below. The pre-earthquake issues of data quality and information flow between CCC and CCL were being revealed by the CES, and the need for accurate pipe information was recognised. Following the severe and widespread impacts to the water network after 22 February 2011, there was a concerted drive to electronically collect comprehensive damage and repair information. CCL commissioned an audit and review of their damage/repair data collection, knowing that inaccuracies in these data were likely to affect the efficacy of future work programmes.

As of early May 2011 approximately 29% of the CCL post-quake database was identified with confidence as being mains or submains (SKM, 2011); accordingly the damage/repair databases were largely considered to be unreliable and therefore personal knowledge of system performance by contractors and CCL personnel was depended upon. Over the last 18 months concerted efforts have been made by CCL and SCIRT to ensure an accurate damage/repair database to support the rebuild programme and inform asset management decision making.

The most recent and updated damage/repair data were obtained from SCIRT's GIS team in March 2013, and form the basis of analyses of pipe damage counts and modes of failure presented in this report.

3.2.2 Methods

Pipe damage assessment - repair counts

Pipe repair count data used here were obtained from SCIRT's GIS team on 11 March 2013, and represent the most accurate picture of the system's spatial distribution and specifications up to this point. The data were in the form of a polyline shapefile, with number of repairs per pipe for the period 5 September 2010 to 5 March 2013 ascribed to each pipe record (see Figure 9). An individual pipe length is defined as a given pipe that does not make significant changes in direction. Where one pipe meets another perpendicularly or obliquely, they are considered two separate pipes (see Figure 2).There is a very large variation in pipe lengths across Christchurch City, and recorded lengths in spatial databases range from 0.1 m to ~2.6 km.

Data were first sorted according to pipe material. Records for Unplasticised Polyvinyl Chloride (UPVC) were merged with those of PVC pipes, based on practitioner understanding of the history and performance of this network component. For each major network pipe material, numbers of repaired pipes, affected lengths, total repairs and repairs per kilometre (repairs km^{-1}) were calculated for each diameter class. Numbers of repaired pipes were assessed by summing all pipe records with at least one recorded repair. Total affected lengths were assessed by summing lengths for pipe records with at least one recorded repair. Total repairs were assessed by summing repair counts for each pipe material. Repairs per km were calculated by dividing total repairs by total pipe length.

Pipe damage assessment according to liquefaction

Comparisons of pipe damage among Liquefaction Resistance Index (LRI) zones (Cubrinovski et al., 2011) were also conducted. The LRI was developed using land damage mapped following the 4 September 2010 and 22 February earthquakes (see Figure 7) in combination with observed ground motions. The development of the LRI is described below (see Cubrinovski et al., 2011 for more details).

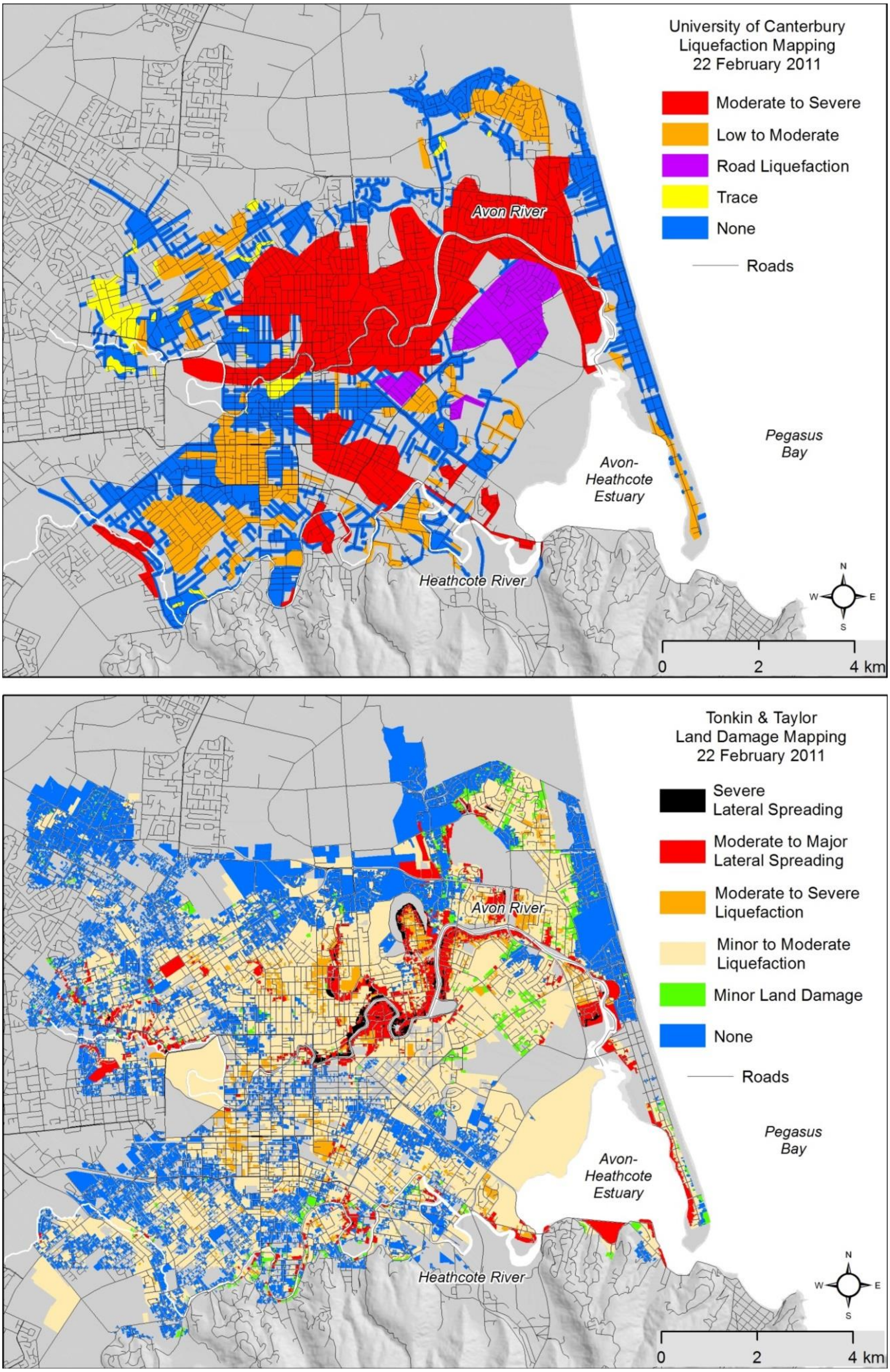


Figure 7. Liquefaction and land damage mapping for the 22 February 2011 Christchurch earthquake. Top: Area-wide interpretations of liquefaction occurrence based on street reconnaissance drive-through conducted by the University of Canterbury (Cubrinovski et al., 2011). Bottom: Property-based land damage assessments conducted by Tonkin and Taylor for the Earthquake Commission.

LRI concept

In the simplified procedure for liquefaction evaluation (e.g. Youd et al., 2001) a factor of safety against triggering of liquefaction (in a free field level ground deposit), *FS*, is calculated as

$$FS = \frac{CRR_{7.5}}{CSR} MSF \tag{1}$$

where $CRR_{7.5}$ is the Cyclic Resistance Ratio or liquefaction resistance while the seismic load (demand) is defined by the Cyclic Stress Ratio (*CSR*) and Magnitude Scaling Factor (*MSF*). Here *CSR* accounts for the amplitude of the seismic load (using the peak ground acceleration as a measure for the amplitude) while *MSF* accounts for the duration of shaking (or number of significant load cycles) using the earthquake magnitude as a proxy for the shaking duration. If $FS \leq 1.0$, then the available liquefaction resistance is smaller than (equal to) the seismic load (demand) and hence liquefaction will be triggered (will occur) for the considered ground motion (earthquake). The simplified method is used as a predictive tool to evaluate the liquefaction potential at a given site for an assumed ground motion (Peak Ground Acceleration, *PGA*; Moment Magnitude, M_w) and estimated liquefaction resistance $CRR_{7.5}$ using empirical relationships based on penetration resistance or shear wave velocity.

Using this approach, the inverse problem could be solved to back-calculate the liquefaction resistance $CRR_{7.5}$ based on records of ground motions and observed liquefaction manifestation due to an earthquake. In the inverse problem, *CSR* and *MSF* are calculated using actual records of peak ground accelerations (*PGA*) and the earthquake magnitude (M_w) respectively, while *FS* is estimated from the observed severity of liquefaction manifestation, and eventually the liquefaction resistance is back-calculated as:

$$CRR_{7.5} = \frac{CSR \cdot \overline{FS}}{MSF} = CSR_{7.5} \cdot \overline{FS} \tag{2}$$

Here $CSR_{7.5}$ is a function of *PGA* and M_w whereas *FS* is a function of the severity of liquefaction manifestation. This approach was adopted to calculate a so-called Liquefaction Resistance Index (*LRI*), produce an *LRI* map and develop liquefaction zoning for Christchurch based on *LRI*, as described below.

There are a couple of advantages of this approach. First, it allows us to quantify actual earthquake observations and summarize them in the form of liquefaction zoning (hazard) map. Second, using this approach we could quickly develop preliminary liquefaction zoning for the needs of CCC and their immediate decision-making before a more robust zoning/analyses based on high-quality geotechnical data could be completed.

$CSR_{7.5}$(wt) values from the Darfield and Christchurch earthquakes

$CSR_{7.5}$ is a function of the PGA on the ground surface, considered depth in the deposit and water table depth, i.e. $CSR_{7.5} = f[PGA, z, wt(z)]$. When the water table is at shallow depths, then the effects of z and *wt(z)* diminish and the cyclic stress ratio effectively reduces to a function of *PGA* alone, i.e. $CSR_{7.5}(wt) = f[PGA]$. Thus, using the geometric mean peak ground accelerations recorded at the strong motion stations within and in the vicinity of Christchurch during the Darfield and Christchurch earthquakes, $CSR_{7.5}(wt)$ were computed at the strong motion stations and then were interpolated across Christchurch using ordinary kriging interpolation.

For the Christchurch potable water system the pressurised pipe network is typically at shallow depths of about 0.8 m, while the wastewater pipes are predominantly at depths from 2.0-3.5 m. In addition, for most of the suburbs that experienced liquefaction in Christchurch, the water table was high, at about 1 m to 1.5 m from the ground surface. For these reasons, the liquefaction zoning for pipe networks was focused on the shallow depths of the deposits corresponding from the depth of the water table to 2 metres below the water table.

Estimated FS values based on liquefaction observations from the Darfield and Christchurch earthquakes

A key issue in the calculation of LRI maps is the assumption/evaluation of the factor of safety *FS.* We have to assume the factor of safety for both areas that did, and areas that did not liquefy during the earthquakes.

For the liquefied areas, the factor of safety was defined based on the severity of manifested liquefaction in the field, as follows. Since triggering of liquefaction yields by definition *FS* = 1.0, traces of liquefaction, low to moderate liquefaction and moderate to severe liquefaction were given *FS* values of 0.9, 0.75 and 0.50 respectively. In other words, *FS* decreases with increased severity of liquefaction manifestation. An *FS* of 0.5 indicates that the available cyclic strength of the soil was half of the seismic load induced by the earthquake. For cases of extreme or very severe effects of liquefaction, an *FS* value of 0.25 was adopted.

In the non-liquefied areas, it was conservatively adopted that in areas where the water table was at 1m or 2m depth, that *FS* was slightly above the threshold triggering value or 1.1 and 1.25, respectively. Then *FS* was increased with the water table depth since it is well known that a thick crust decreases the likelihood of occurrence and surface manifestation of liquefaction. Thus, *FS* = 1.5, 1.75 and 2.0 was adopted for areas with depth to water table of 3.0, 4.0 and 5.0m.

This approach was applied to establish an LRI map for Christchurch using the liquefaction maps shown in Figure 7 and $CSR_{7.5}(wt)$ distribution calculated based on the magnitude and recorded PGAs for the Darfield and Christchurch earthquakes. Note that the UC liquefaction map (Fig. 7, Top) was the principal map used in the evaluation of LRI, and the T&T map (Fig 7, Bottom) was employed only in areas that were not covered by the UC map. By multiplying the *FS* values with the respective $CSR_{7.5}(wt)$ the LRI value was calculated and summarised in Figure 8 in the form of a Liquefaction Resistance Index map of Christchurch. Here orange, yellow, green and blue indicate Zones 1, 2, 3 and 4, with Zone 1 being the reference zone. The red zone covers predominantly the abandoned areas or the Residential Red Zone and is below the established threshold LRI value of 0.065. Note that the zone numbers also indicate the relative liquefaction resistance. Thus, for example, Zone 3 has three times the liquefaction strength of the lower bound value of Zone 1.

To further facilitate the use of the LRI map in preliminary design evaluations, Table 2 summarizes the typical range of settlements, ground displacements and strains associated with each *LRI* zone. These are based on expert judgement and should be taken only as preliminary estimates with further updates to follow based on more robust interpretation and analysis.

For the grey zone, there were no liquefaction observations/inspections, and therefore these areas are outside of the *LRI* zoning, and should be considered/evaluated separately.

Pipe damage analysis

The damage to the pipe network was correlated to the *LRI* zones using the methodology described below. To avoid difficulties where an individual pipe traversed the boundary between two LRI zones, the mid-point of each pipe was defined (half-way along pipes of any length) and intersected with the LRI map (see Figure 10). For each major network pipe material within each LRI zone numbers of repaired pipes, affected lengths, total repairs and repairs per km were calculated for each diameter class.

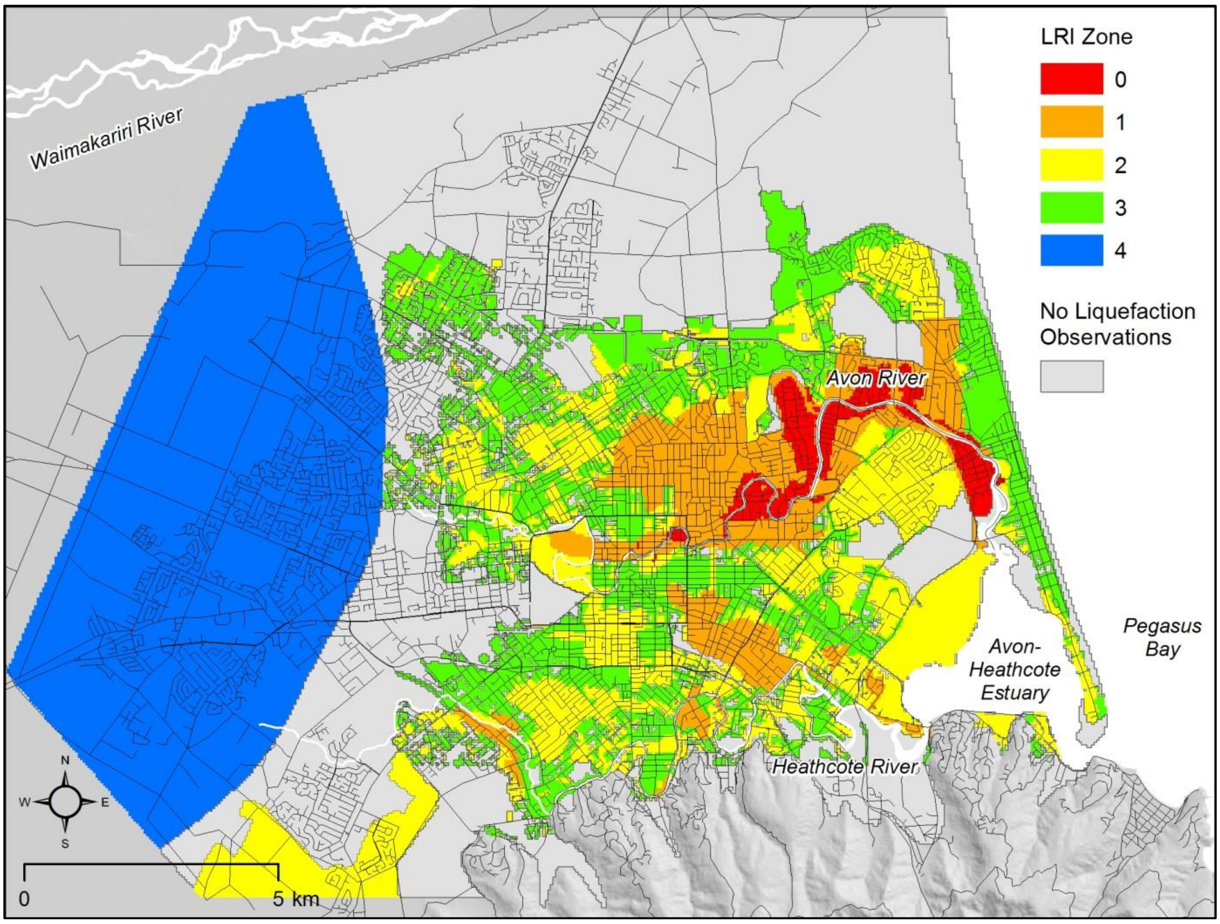


Figure 8. Liquefaction Resistance Index (Zoning) for Christchurch City. Associated ground deformations are shown in Table 2.

Table 2. LRI Zones and associated ground deformation (settlements, lateral displacements and strains).

LRI Zone	Equivalent CRR	Representative LRI (at water table)	Ground settlement (mm)	Lateral displacement (relative; transient) (mm)	Assumed ground strains and thickness of liquefied layer
0	< 0.065	-	> 500	> 400	$\varepsilon_v > 5\%$, $\gamma > 4\%$, H_L=5 – 10m
1	0.065 – 0.11	0.065	250 – 500	200 - 400	$\varepsilon_v = 5\%$, $\gamma = 4\%$, H_L=5 – 10m
2	0.11 – 0.16	0.13	50 – 250	40 - 200	$\varepsilon_v = 3\%$, $\gamma = 2\%$, H_L=4 – 8m
3	0.16 – 0.23	0.195	20 – 50	20 - 40	$\varepsilon_v = 1\%$, $\gamma = 1\%$, H_L=2 – 4m
4	> 0.23	0.26	< 20	< 20	$\gamma < 0.5\%$, H_L=0m

- Design should accommodate the higher value of displacement/deformation

- ε_v = volumetric strain, γ = shear strain

- The table and LRI map are for preliminary use and restricted to the water / wastewater systems of Christchurch

Pipe damage assessment - modes of failure

Modes of failure were determined using contractor descriptions of repair jobs within an updated and cleaned CCL point database of pipe repairs. Some contractor comments required clarification with CCL staff. Each job record was assessed for information on the nature of pipe damage and/or information on materials used in the repair, or if there was no useful information on either of these aspects. Those records where pipe damage was described were further classified into two classes: damage to the pipe itself, and damage to fittings.

The repair database did not contain specific information on pipe materials or diameters. This information was assigned to the individual repair records from the SCIRT repair count database (Figure 9), using each pipe's unique identifier code to join the two datasets (i.e. for properties and damage, respectively). This process revealed that ~200 records had discrepancies between pipe material as stated in the repair count data and that described by contractors who conducted repairs. These discrepancies accounted for ~13% of GI repairs that were mis-classified as HDPE. The main reason for these discrepancies, as described earlier, was due to small sections of repair material

(HDPE) being ascribed to the whole GI pipe lengths when the electronic records were updated by CCC. For this analysis and that of the peak ground acceleration analysis presented below, the contractors' descriptions of pipe materials were considered accurate, and therefore used. After reviewing the data a total of 6094 classified repair records were assessed as suitable for this analysis. The final repair data were also used for establishing the time lines of repair jobs presented in Figure 12 and Appendix D.

Water network trenches

Pipe trench characteristics have also changed over time (Figure 3). From the first development of the network, trench backfill material was either the locally excavated soil material if soil particle size was appropriate (sands through to fine gravels), otherwise fine gravel material was imported from quarries situated on the city margins. From 1984 trench construction was standardised so that all pipes were emplaced in a sand layer covered with AP40 gravel mix. There was a programme of backfill compaction testing to identify the optimum mix to prevent trench settling, which was impacting road surfaces. From 2005 an AP20 gravel mix has been used, as it was determined to be less abrasive and damaging to pipe materials than the AP40.

A preliminary interpretation of spatial variability in trench construction across the Christchurch City urban area was developed here. Using the mapped soil data of Webb et al. (2010), descriptions indicating soil textures from sandy to loamy gravels were identified as areas of locally excavated trench backfill materials; other soil textures including dominantly loamy soils and peats were identified as areas of imported trench backfill materials. These two classes were assigned to those sections of the pipe network installed prior to 1984; installation dates were also used to identify areas of AP40 and AP20 fill.

Peak ground acceleration

Spatial distribution of PGA was computed by Bradley and Hughes (2012) based on strong-motion station records for 4 September 2010, 22 February 2011, 16 April 2011, 13 June 2011 (two events) and 23 December (two events). The PGA data were interpolated to a 100 m-resolution grid, and across the spatial extent of the water supply network a 1 km grid was generated (Figure 11a). Within each 1 km grid cell a series of regular sampling points (100 per 1 km grid cell) was generated to sample the 100 m-resolution PGA grid (Figure 11b). Mean PGA values were calculated from the 100 sample points and then ascribed to their bounding 1 km grid cell (Figure 11c). For both 13 June 2011 and 23 December 2011 where there were two major earthquakes on each of those days, and thus the highest mean PGA value experienced that day within a given 1 km grid cell was used in the analysis.

In order to illustrate the above methodology, a preliminary analysis of AC repair rates versus PGA is provided here. For each 1 km grid cell the total length of AC pipe was calculated, and for each CES event under consideration the number of AC repairs within the 1 km grid cells were summed (Figure 11d). This analysis does not discriminate between AC pipe diameters, nor does it discriminate between repairs to the pipe body versus pipe fittings.

To further assess pipe damage against ground performance, the 1 km grid cells were assigned to a LRI zone (Cubrinovski et al., 2011) (Figure 11e). This was achieved by determining which LRI zone comprised the greatest fraction of each 1 km grid (Figure 11f).

Note that the above methodology was adopted for preliminary analysis, and that further analyses using a more rigorous methodology are currently under way.

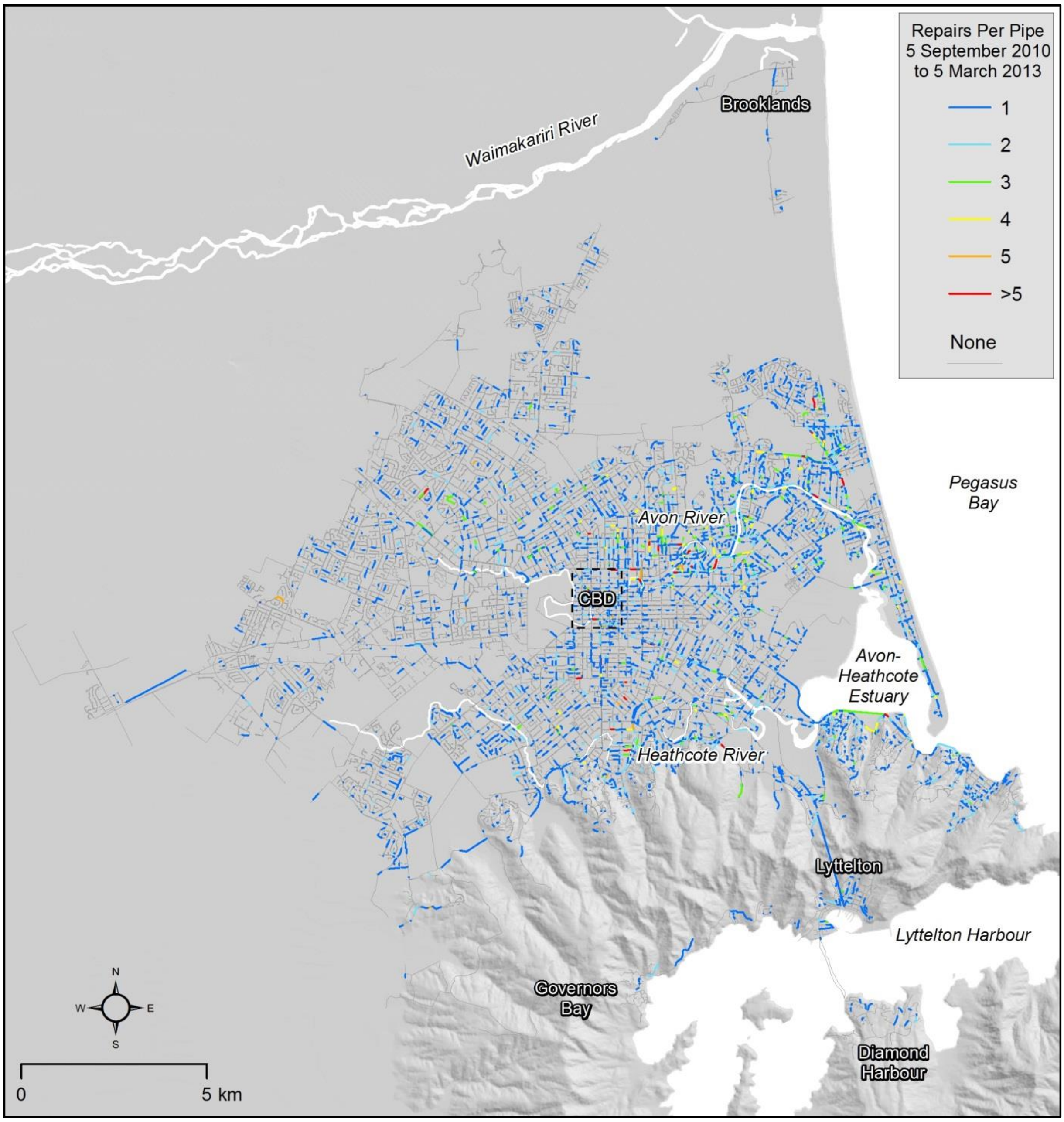


Figure 9. Numbers of repairs per pipe in Christchurch City and Lyttelton Harbour over the period 5 September 2010 to 5 March 2013.

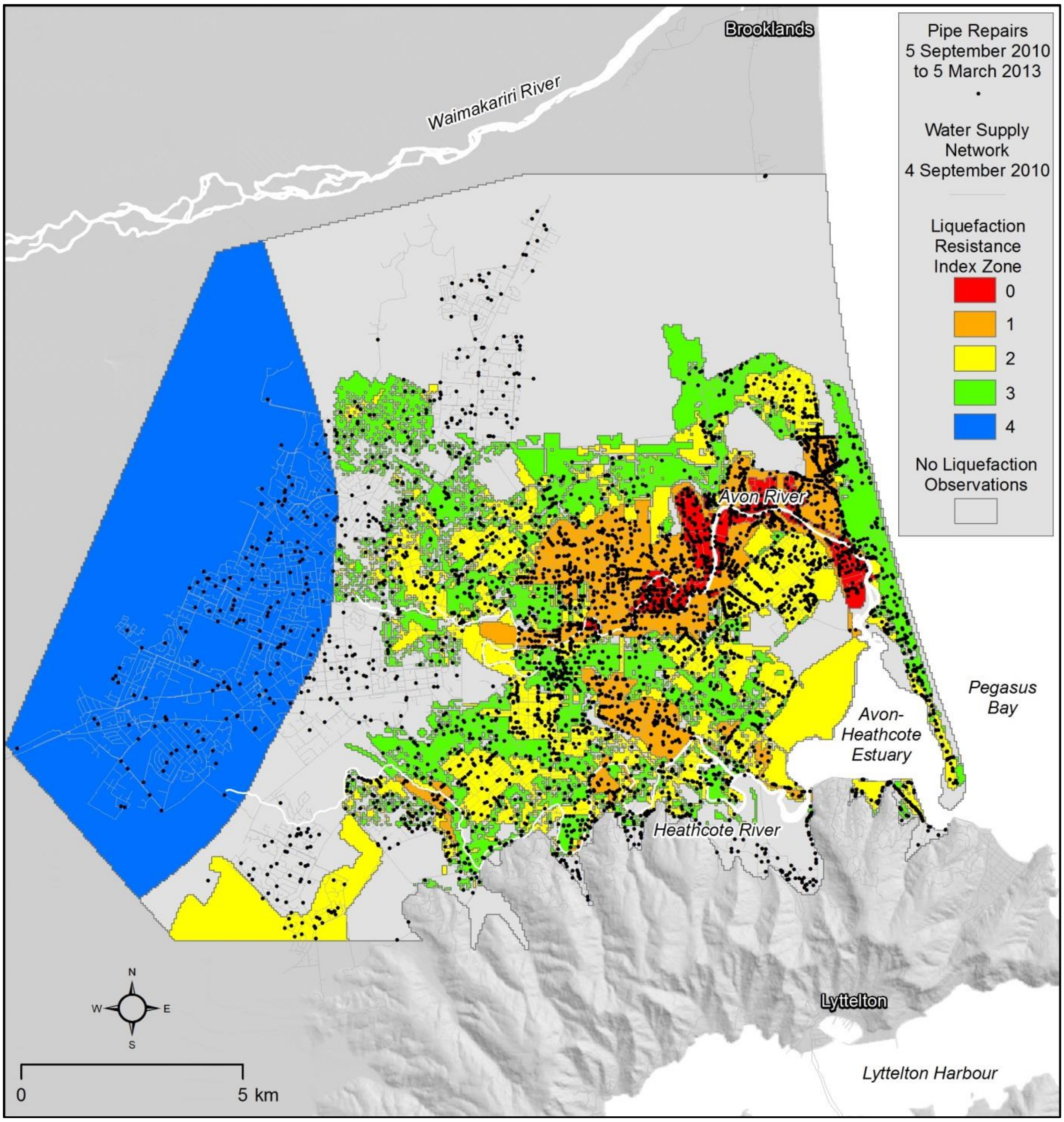


Figure 10. Locations of repaired potable water pipe midpoints within the LRI analysis area, and LRI zones.

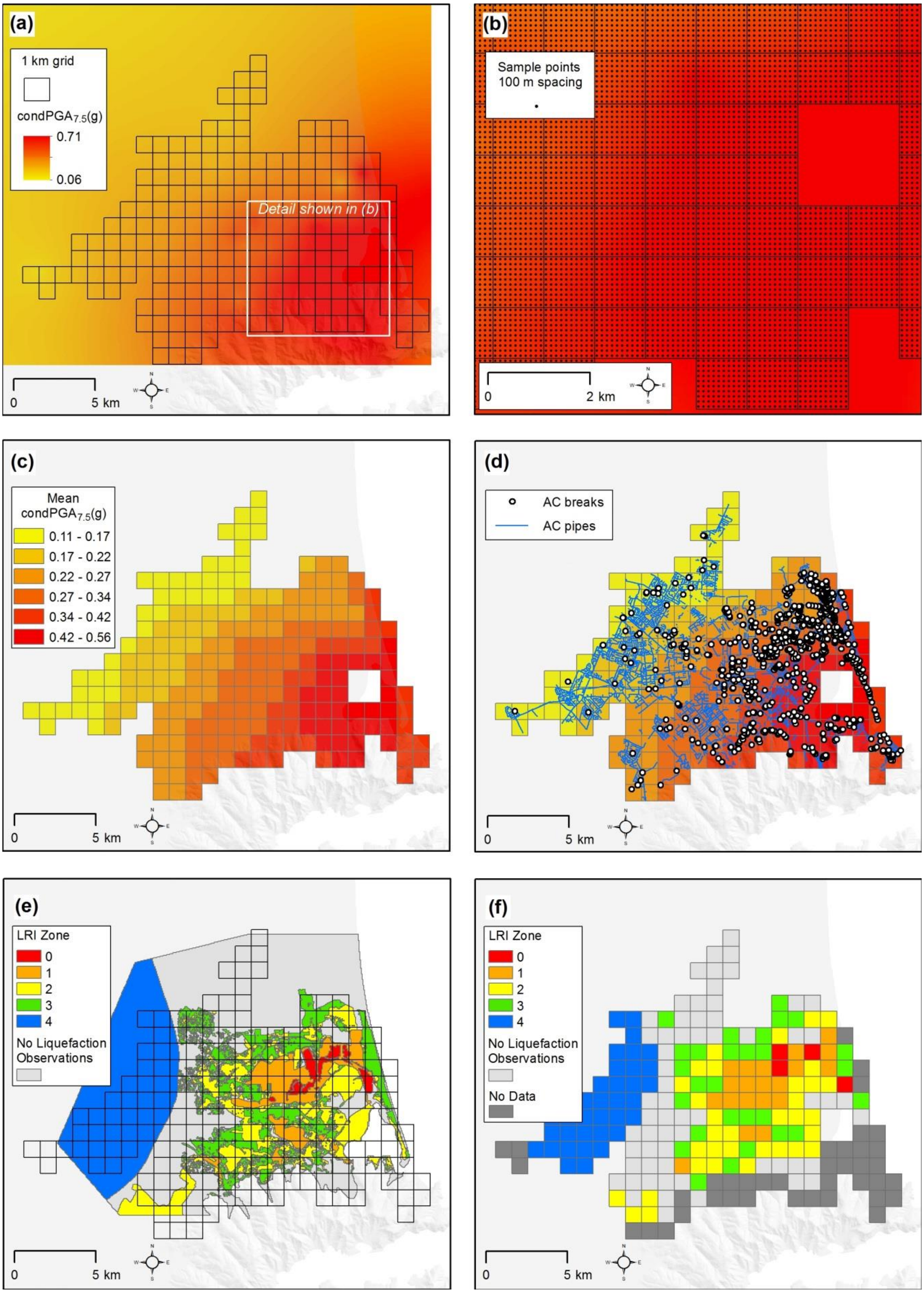


Figure 11. Method for AC pipe breaks PGA analysis, using 22 February 2011 as an example. (a) Interpolated PGA (100 m resolution) across the Christchurch region (Bradley and Hughes, 2012), with the city area divided into 1 km grid cells. Grid cells covering the extent of the AC pipe network are shown. (b) Within each 1 km grid cell, 100 points were generated to sample the PGA model. (c) The mean PGA calculated from the 100 sampling points was ascribed to each 1 km grid cell. (d) For each 1 km grid cell, total length of AC pipe and total number of breaks AC were determined. (e) In addition, each 1 km grid cell was assigned to a LRI zone (Cubrinovski et al., 2011), based on which LRI zone comprised the greatest spatial extent within each grid cell (f).

3.2.3 Results

Pipe Repair Time Line

Previous studies have highlighted the frequency of water network repairs through the CES (O'Rourke et al., 2012, 2013; Cubrinovski et al., 2013). Prior to the CES, the Christchurch water network repair rate was approximately 0.5 per day. Following each major earthquake event the initial repair frequency was very high, with an average of 40 repairs per day in the first three weeks after the earthquake, with a reduction to approximately 2-3 repairs per day after 50 days.

Here we present updated daily repair counts and cumulative repair plots for the period 5 September 2010 to 30 June 2012 (Figure 12). As seen in previous summaries (O'Rourke et al., 2012, 2013; Cubrinovski et al., 2013) there were significant numbers of repairs in the weeks after 22 February 2011 and 13 June 2011, but no apparent comparable increase after 23 December 2011.

In Appendix D are presented timelines of CCL repairs disaggregated into pipe materials and diameters, along with Canterbury region earthquake Moment Magnitudes (M_w) from 4 September 2010 to 30 June 2012. There was little systematic recording of repair jobs after initiation of the CES on 4 September 2010. However after 22 February there was a clear increase in recorded repair jobs for most pipe types. Over the two weeks after this event GI submains repairs peaked at >60 repairs in one day, and AC mains repairs peaked at >50 repairs in one day. CI mains, HDPE submains/crossovers and MDPE80 submains/crossovers also showed a distinct increase, but with fewer overall repairs. For GI, AC, CI and MDPE80 there was also a distinct but less pronounced increase in repair rates after 13 June 2011 and even less so after 23 December 2011. PVC, MPVC and MDPE80 showed very low repair rates. When viewed from the perspective of pipe diameters, the repair rates reflect the most commonly used spatially/extensively pipe diameter for a given pipe material. Repairs for all materials occurred not just the weeks following each major event, but continued at lower rates in the following months throughout the CES up to 30 June 2012.

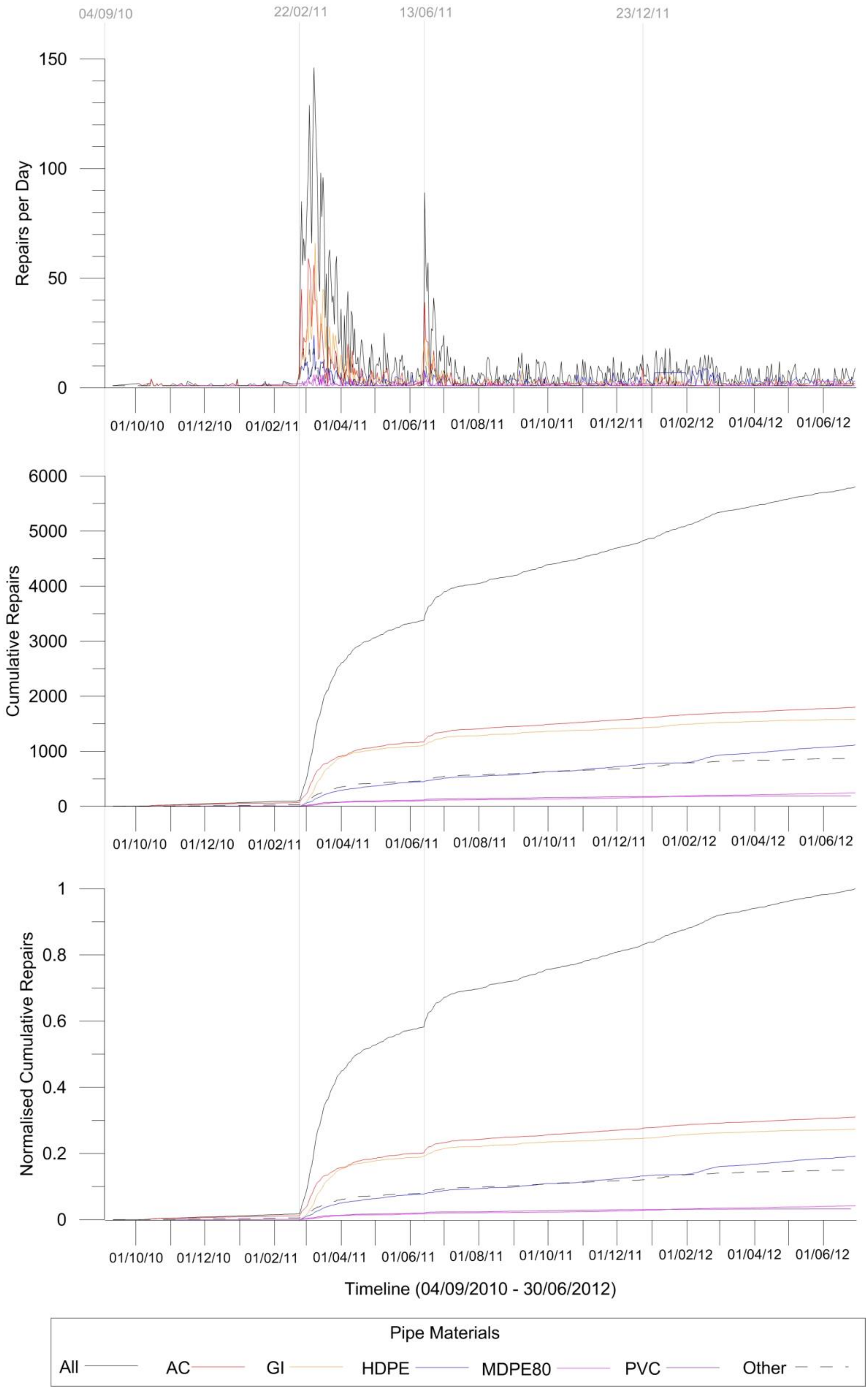


Figure 12. Daily potable water repairs through the CES, presented as daily counts (top), cumulative counts (middle) and normalised cumulative counts (bottom).

Pipe Repair Rates According to Material, Diameter and Liquefaction Resistance Index Zoning

Repairs for pipe materials across Christchurch City and Banks Peninsula are presented in Figure 13 in order of increasing repairs km^{-1}. MPVC, PVC, MDPE80 and DI had <1 repair km^{-1}, HDPE had 1.9 repairs km^{-1}, AC and S had 2.3 and 2.7 repairs km^{-1}, respectively, CI and CLS both had 3.2 repairs km^{-1}, and GI had the highest rate of 8.9 repairs km^{-1}.

Establishing definitive differences in repair rates between pipe diameters within a given pipe material type is problematic due to unequal total lengths, and the fact that materials for different network components are usually restricted to only a few diameter classes. However, PVC pipes have been used as both submains/crossovers (40 mm and 50 mm diameter) and mains (100 mm, 150 mm and 200 mm diameter) of sufficient length to enable comparison (Figure 14a). Submains repair rates ranged 0.7-1.0 repairs km^{-1}, and 100 mm diameter mains also had a rate of 0.9 repairs km^{-1}. With increasing mains diameters there is a distinct decrease in repair rate, with 150 mm diameter pipes having a rate of 0.6 repairs km^{-1}. Highest repair rates were for 25 mm (0.9 repairs km^{-1}, although these comprise only ~3% of the PVC network) and 40 mm diameter (1.0 repairs km^{-1}) submains, and 100 mm mains also had a rate of 0.9 repairs km^{-1}. Mains of 150 mm diameter had a rate of 0.6 repairs km^{-1}. Repair rates further decreased with increasing diameter: 175 mm and 200 mm diameter mains both had a rate of 0.4 repairs km^{-1}, and 300 mm diameter mains had a rate of 0.3 repairs km^{-1}.

Up to the commencement of the CES on 4 September 2010, AC pipes comprised a significant component of Christchurch's mains system (approximately 771 km length). Different AC diameters showed distinct differences in repair rates (Figure 14b). 100 mm mains had a rate of 3.1 repairs km^{-1}, 150 mm and 200 mm pipes and similar rates of 1.7 and 1.8 repairs km^{-1}, respectively, and 300 mm diameter pipes had a rate of 1.2 repairs km^{-1}. See Appendix C for all tables of repair rates for each diameter class within each pipe material category.

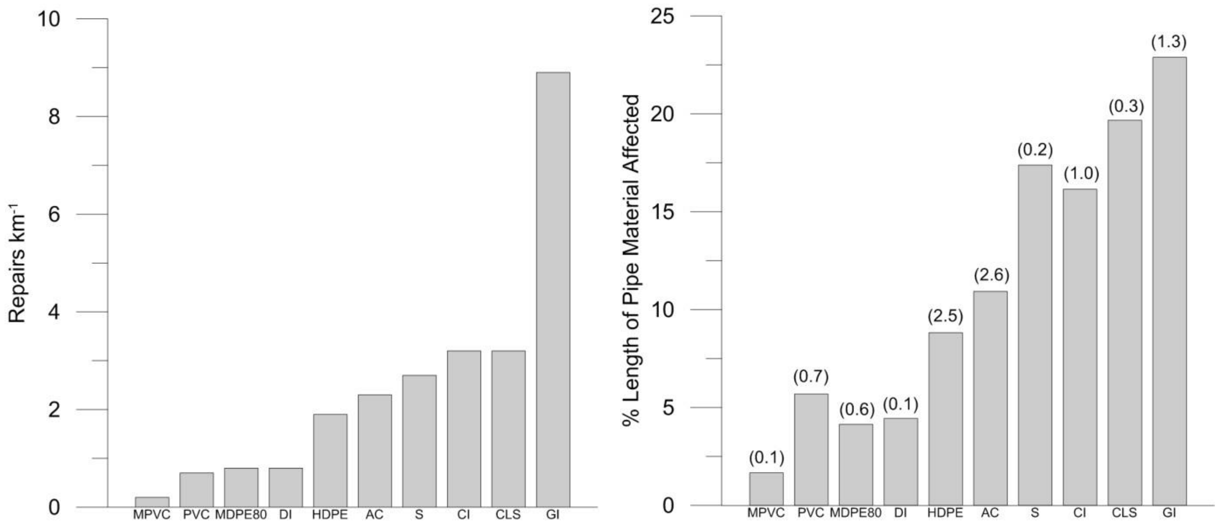


Figure 13. Left: Summary repair data for different pipe materials. Right: Percentage length of each pipe material affected by CES damage. Affected percentage length of the the entire network is presented in parantheses.

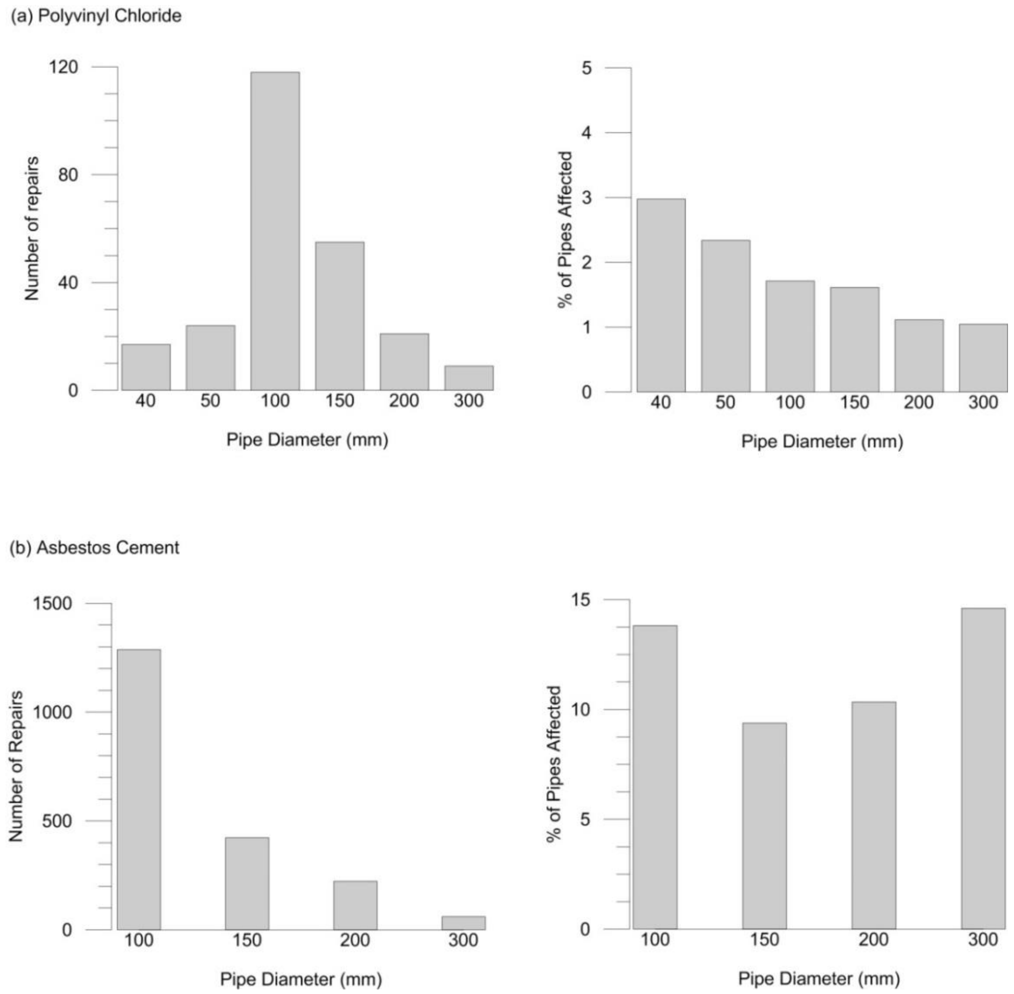


Figure 14. Repair data for PVC (a) and AC (b) pipes according to pipe diameters. Data cover the period 5 September 2010 to 5 March 2013.

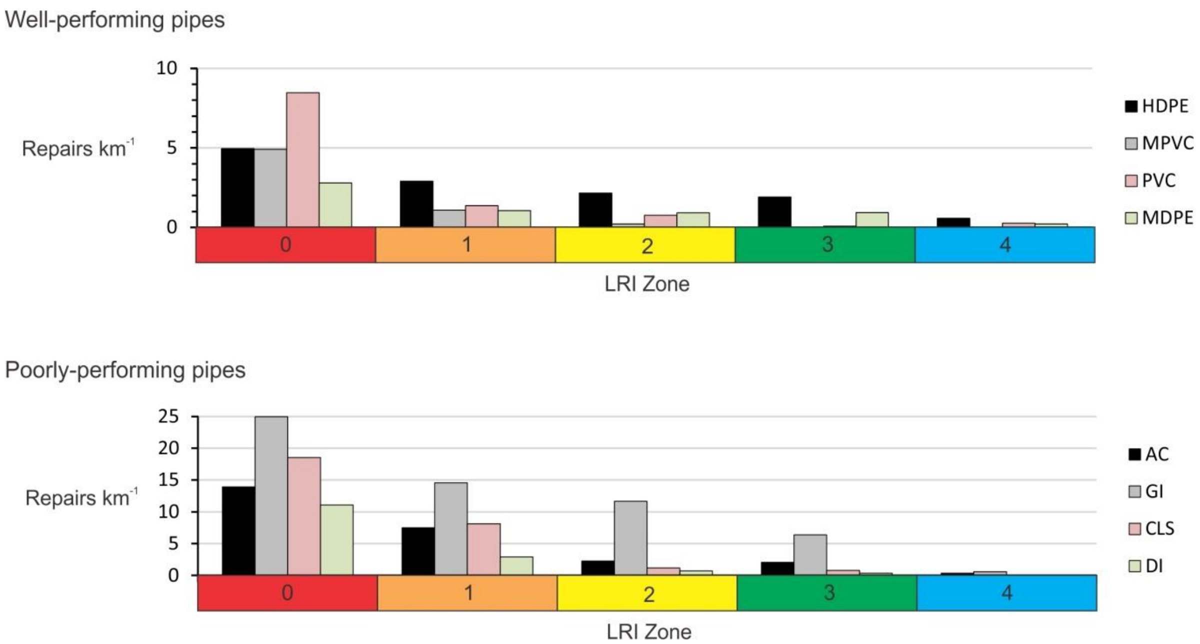


Figure 15. Summary repair data for the potable supply network within Liquefaction Resistance Index zones (see Figure 10). Data cover the period 5 September 2010 to 5 March 2013.

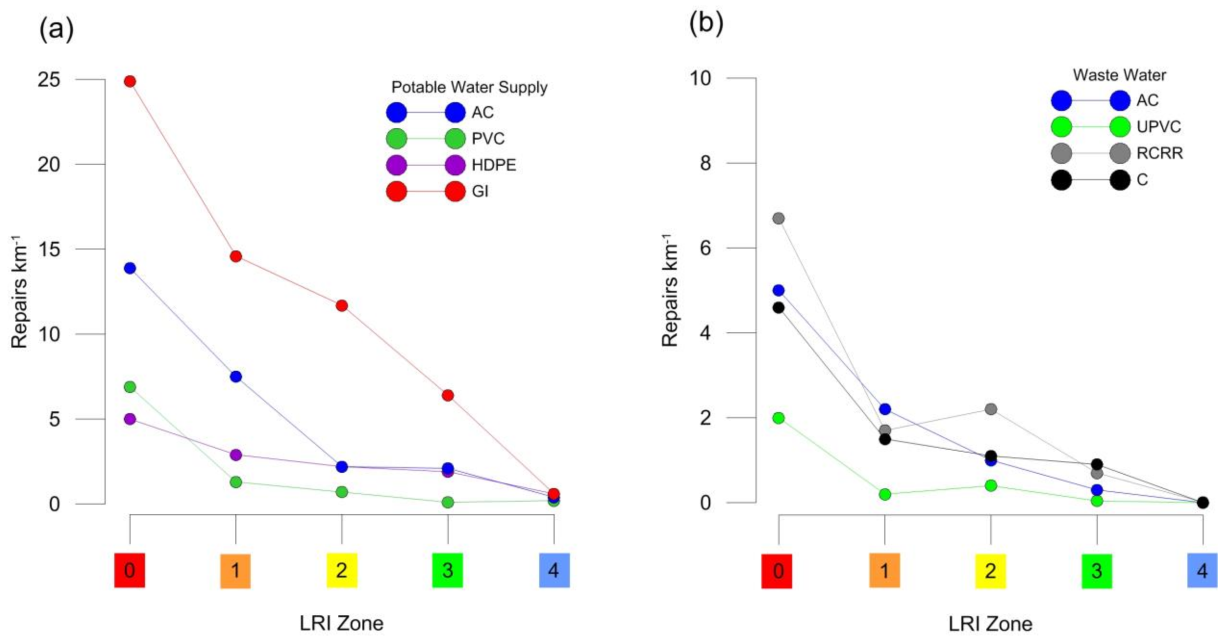


Figure 16. Summary repair data for dominant pipe materials for the potable water supply system (a) and the waste water system (b) in different LRI Zones. AC= Asbestos Cement

A subset of the water network repair data within the LRI analysis area (Cubrinovski et al., 2011; 2013) shows clearly that for all pipe material types, there is a consistent decrease in repair rate from LRI Zone 0 to LRI 1 (Figure 15 and Figure 16) and further decrease in repair rates with increasing liquefaction resistance (*LRI*). Unfortunately the highly variable numbers of pipes with different diameters with LRI zones makes it problematic for rigorous comparisons with regard to pipe diameters. However, data indicate that there is an overall decrease in repairs km^{-1} with increasing pipe diameter, particularly for PVC and AC (Appendix E).

Trench Backfill Characteristics

Figure 17 presents trench backfill characteristics across Christchurch City. This is a simplified presentation based on the year of construction which does not consider details such as particularities of quarried gravels used through the decades, and pipes installed by direct drilling methods. Yet the data illustrates the trench backfill spatial complexity, within which the water network of differing pipe materials of varying age is embedded. Through the CES there have been examples of trench materials that have retained their integrity through multiple earthquakes and liquefaction events, evidenced by upraised trenches in road surfaces that had largely settled through compaction. A better spatial characterisation of trench materials would aid understanding of pipe performance through the CES including the benefit or lack of it when using a particular backfill material.

With these caveats in mind, some trends are evident in the trench data (Figure 18). For AC pipes in LRI Zones 0-3, repair rates are consistently higher in native soil backfills then for imported gravels or AP40 mix. HDPE repair rates are also highest in native soils in LRI Zones 0 and 1, but in LRI Zones 2 and 3 repair rates are lower in native soils than for imported gravels and AP40 mix. GI pipe repairs per km in LRI Zone 0 are highest in AP40 mix, and significantly lower for imported gravels and native soils, whereas for LRI Zones 1-3 the highest repair rates are in imported gravels backfill.

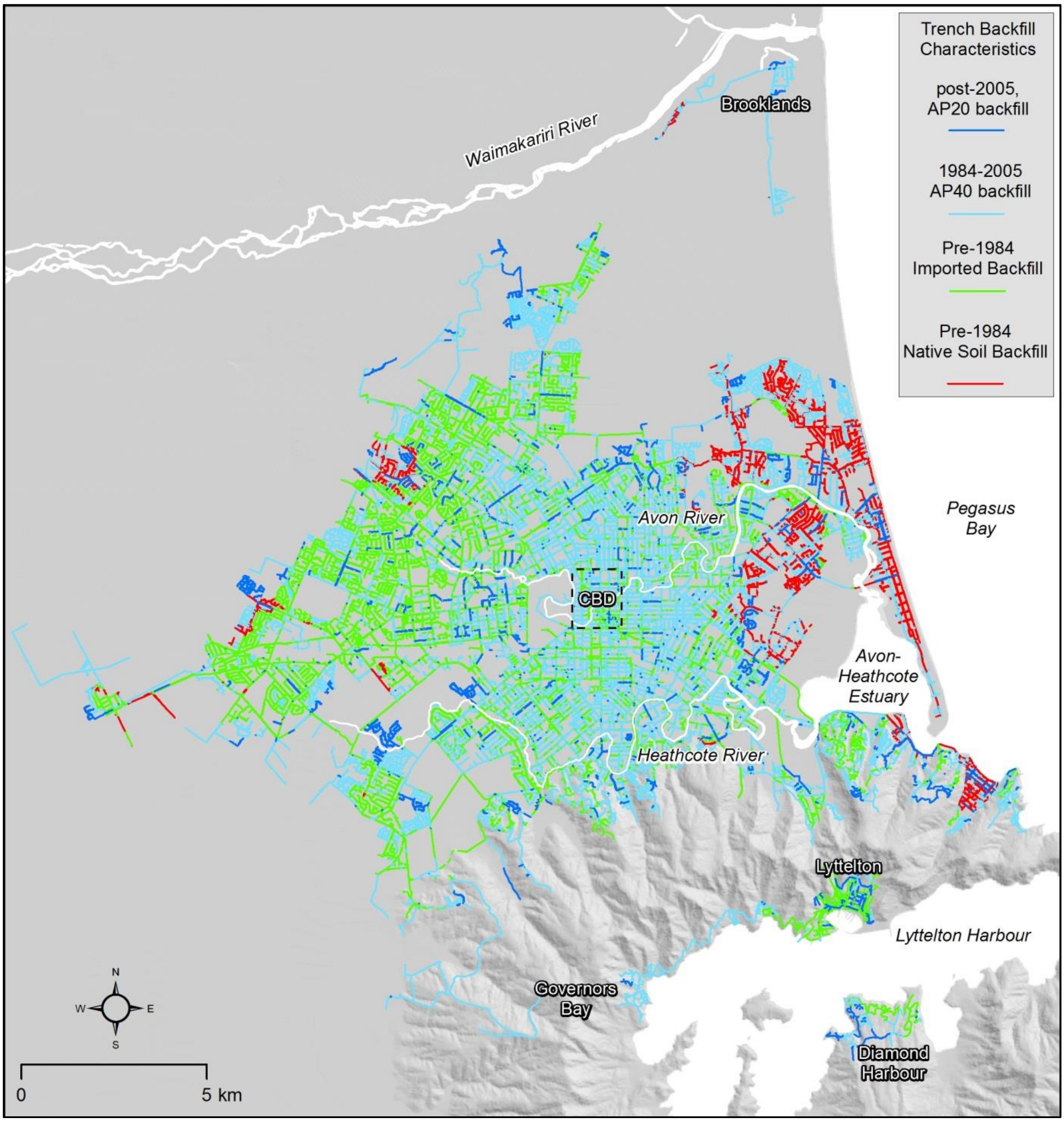


Figure 17. Trench backfill characteristics for the potable water system in Christchurch City and Lyttelton Harbour.

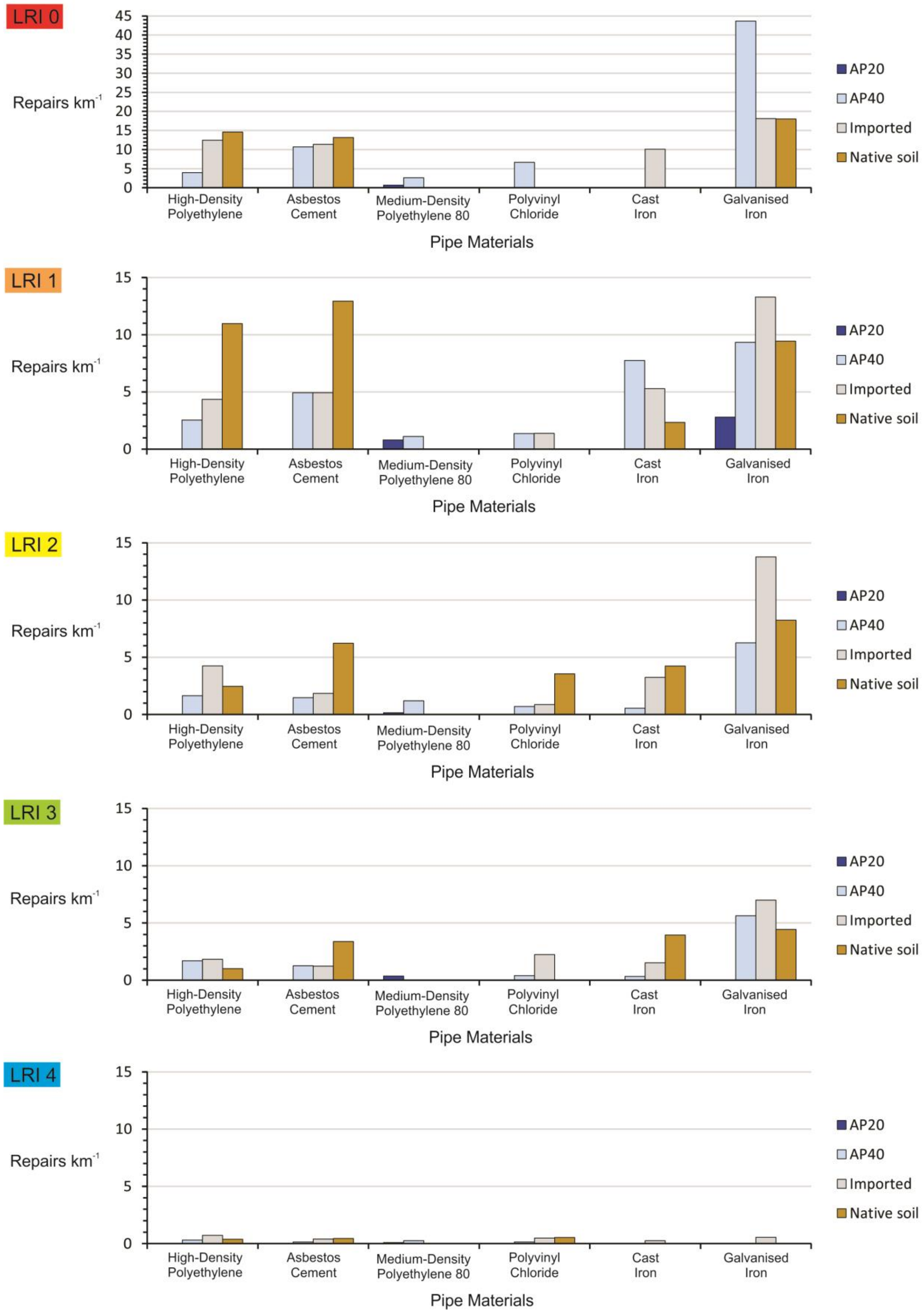


Figure 18. Pipe material repair rates for trench backfill characteristics within each LRI Zone.

Modes of Failure

Pipe repair records were initially classified into three categories: nature of damage to the pipe itself, type of damage to pipe fittings, and no damage information (unspecified faults). Across all pipe damage repair records reviewed, (n=6094), 21% specified pipe damage, 35% specified fitting damage, and 44% contained no useful damage information. There was considerable variation between pipe materials in the damage information described (Figure 19).

Based on known failure modes, AC was the only pipe material where most of the damage was to the pipe itself (62%) compared to fittings (38%). For all other major pipe materials, the dominant failure modes occurred on pipe fittings (HDPE = 82%; MDPE80 = 90%; PVC = 80%; CI = 79%; GI = 58%).

Definitions of damage categories are provided in Table 3, further details of failure modes are presented in Figure 20, and examples of pipe damage and fittings are presented in Figure 21 - Figure 32. As shown in Figure 20, for AC and GI pipe the dominant failures are to the pipe body, with circumferential and longitudinal splits relatively common for AC, and pinhole repairs relatively common for GI. For the remainder of pipe materials most failures were to fittings, with damage to property connection, coupler and gibaults most common.

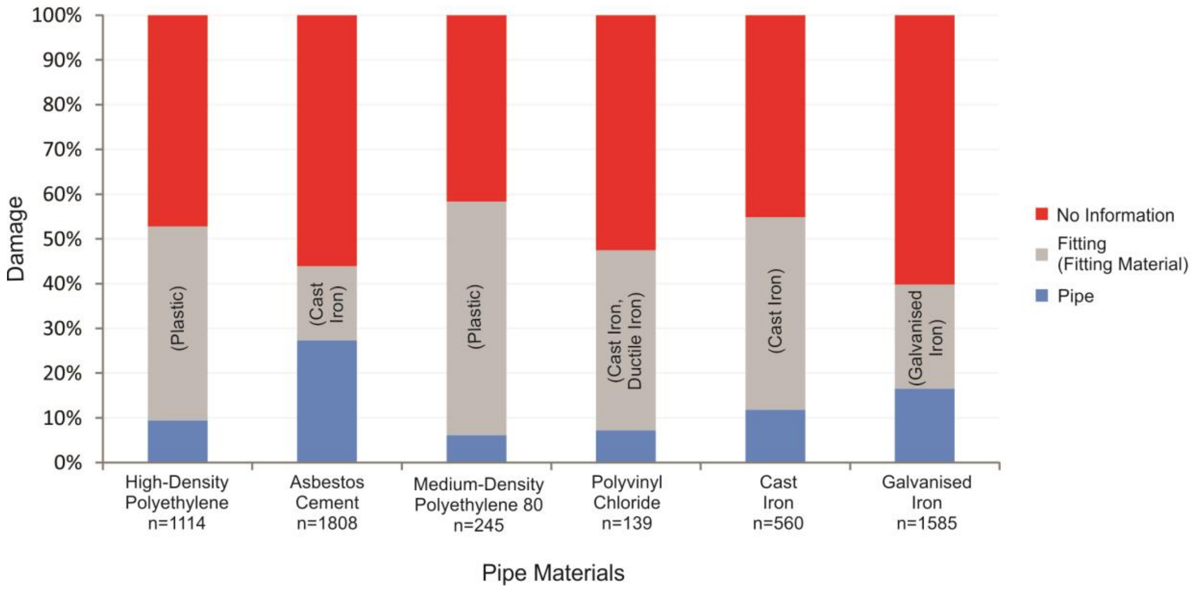


Figure 19. Major damage categories for different pipe materials through the CES over the period 4 September 2010 to 30 June 2012. The dominant fitting materials used for each pipe material are noted in parentheses.

Table 3. Definitions of most commonly occurring pipe failures.

Pipe Damage Category	Definition
Blown	Section of the pipe wall blown outward. Also referred to as "bursts" by repair contractors.
Circumferential Split	Also referred to as a "broken back", "ring crack" or "snapped" by repair contractors. The pipe has split around its circumference leading to complete failure, sometimes accompanied by horizontal or vertical misalignment of the separated pipe sections. Most common in AC mains. See Figure 21.
Collar	Sleeve of material the same as that of the pipe body, used to connect two pipes. Commonly fractured or disintegrated. Specific to AC, PVC and CLS mains. See Figure 22.
Longitudinal Split	Usually referred to as "split" by repair contractors. Pipe has split parallel to its length, often along pipe seams. See Figure 22 and Figure 23.
Pinhole	Very small holes, often only visible when pipe is pressurised. Most often found in GI submains.
Unspecified break	Potentially one of the above damage modes to the pipe body but repair contractor has not specified which.
Fitting Damage Category	**Definition**
Bend	Also known as "elbow", a curved section to enable change of pipe direction. See Figure 27.
Coupler	Connects two pipes, often broken or loose.
Gibault	Connects two pipes, often broken or loose. See Figure 28.
Lead Joint	Malleable lead seal used to join two pipe sections. Usually squeezed from original configuration by pipe movements and able to be hammered back into place. Specific to CLS and CI mains.
Pipe Connection	Also referred to as "saddle" by the industry. Connects submains/crossovers to mains. Fitted around circumference of main. Often broken or loosened. See Figure 29.
Property Connection	Also referred to as "tapping band" by the industry. Same function/configuration as pipe connections but connects submains to lateral pipes supplying properties. Often broken or loose.
Tee	Connects a given pipe to two others perpendicular to it. See Figure 30.
Valve/Gate Valve	Valves enable closing/opening of mains water flow. Gate valves enable closing/opening of submains water flow to properties. See Figure 30.
Previous repair	Often comprised of repair clamps (see Figure 31) that need re-tightening or replacing. Can include Gibault-PVC combinations (Figure 28) that replace broken section. Difficult to ascertain with certainty is the previous repair if from earthquake damage or failure prior to the CES.
Unspecified fitting	Potentially one of the above fitting damage modes but repair contractor has not specified which.

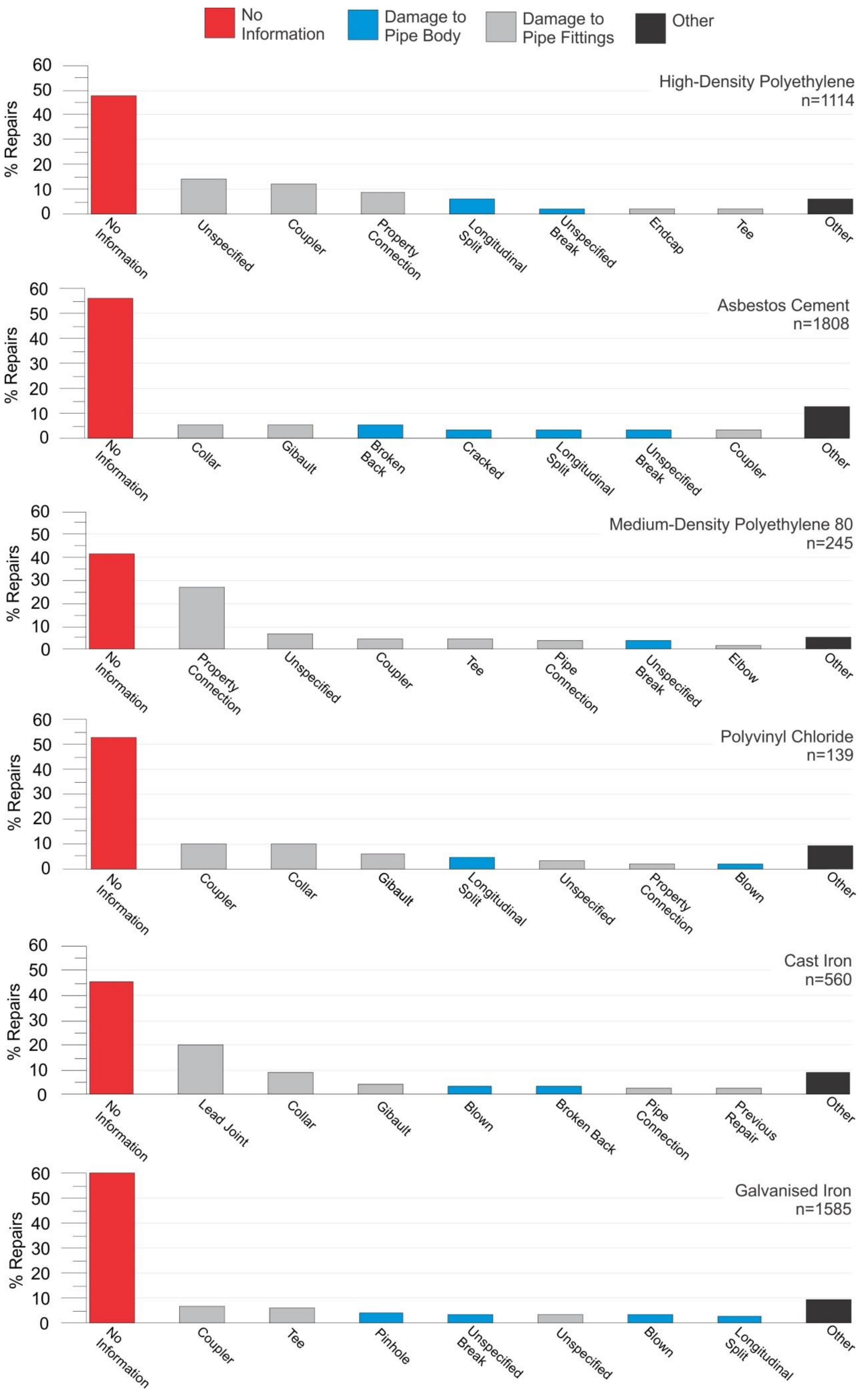


Figure 20. Failure modes for major potable water pipe materials for the period 4 September 2010 to 30 June 2012. Further details are presented in Appendix G.

Figure 21. Circumferential split (indicated) on AC main, Rowan Avenue. Photo: Courtesy of Hugh Blake-Manson, CCL.

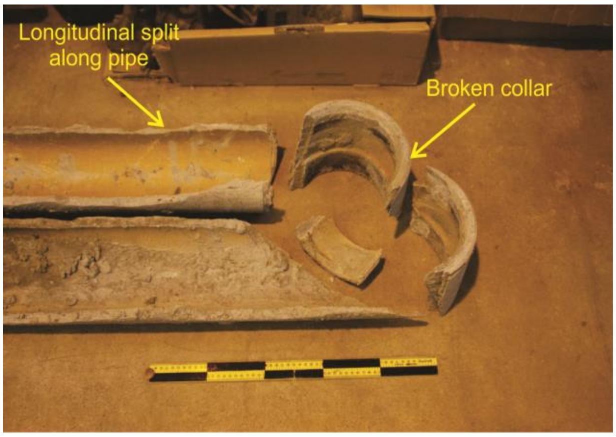


Figure 22. AC main broken collar and longitudinal split. Photo: M. Hughes.

Figure 23. Longitudinal split on AC main. Photo: M. Hughes.

Figure 24. Broken CI main. Photo: M. Hughes.

Figure 25. Bursts in the wall (indicated) of a CLS main. Photo: M. Hughes.

Figure 26. PVC mains. Photo: M. Hughes.

Figure 27. Mains bend. Photo: M. Hughes.

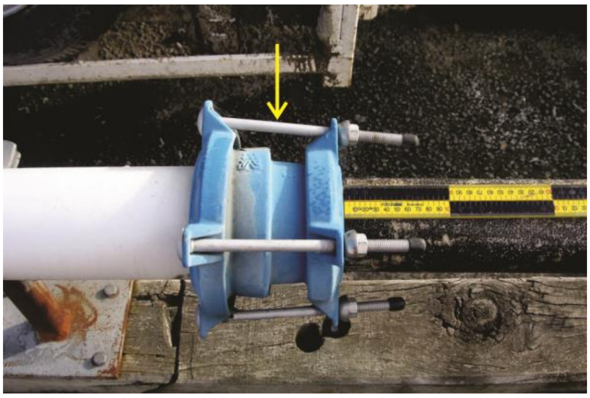


Figure 28. Gibault (indicated) joining two pipes. Photo: M. Hughes.

Figure 29. Pipe connection (indicated), into which submains are connected. Photo: M. Hughes.

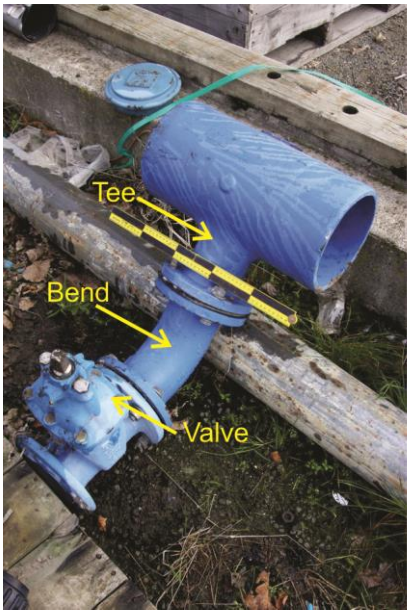


Figure 30. Mains tee, bend and valve. Photo: M. Hughes.

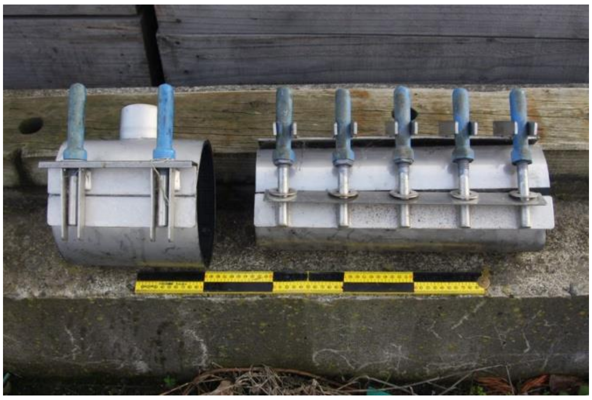


Figure 31. Repair clamps. Photo: M. Hughes.

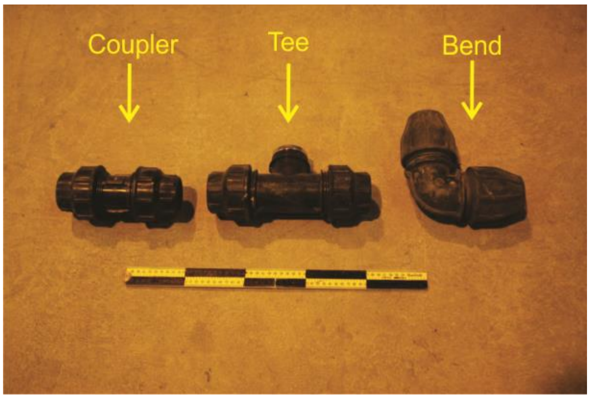


Figure 32. Submains fittings: coupler, tee and bend. Photo: M. Hughes

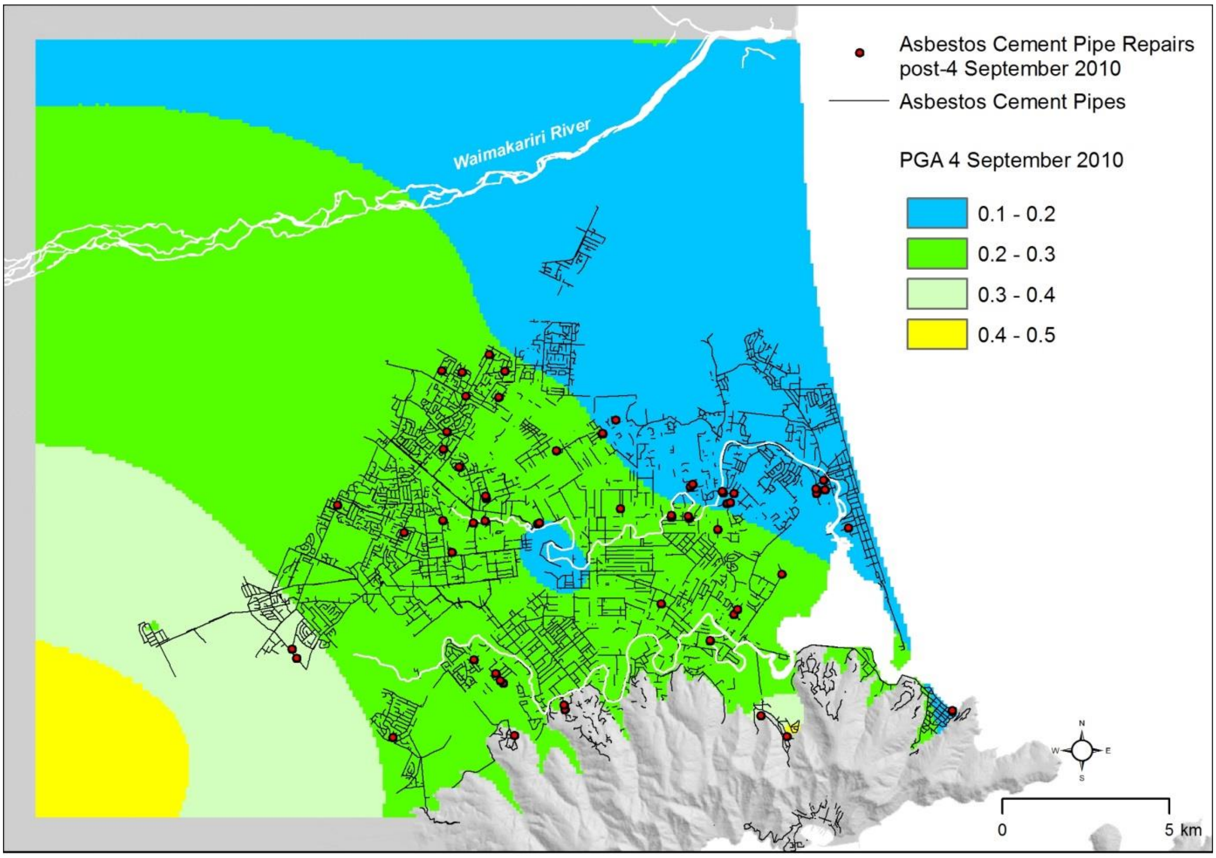
Peak Ground Acceleration and Ground Performance

The spatial distribution of PGA and magnitude-weighted $PGA_{7.5}$ for 4 September 2010, 22 February 2011, 13 June 2011 and 23 December 2011 is shown in Figure 33 to Figure 36, along with AC pipe repair locations in the weeks and months after each event up to the following large aftershock (post-23 December 2011 repairs extend to 30 June 2012). It is evident that post-22 February 2011 AC repairs were the most numerous, with clusters of AC damage in areas corresponding to high PGAs and associated permanent ground deformations. There appears to be similar spatial clustering post-13 June 2011, but AC damage locations are more evenly spread across the Christchurch urban area post-4 September 2010 and post-23 December 2011.

Results of the AC breaks km^{-1} versus $PGA_{7.5}$ analysis are shown in Figure 37. Shown here are results only for those 1 km grid cells where there was at least 1 repair km^{-1}, and results are not shown from grid cells with no AC damage. The $PGA_{7.5}$ experienced by damaged AC pipes and associated pipe breaks fall into distinct clusters depending on CES event (see top graph in Figure 37), which reflects distance from the causative faults: 4 September 2010 $PGA_{7.5}$ ranged 0.16 to 0.34 g, with a maximum of 1.8 breaks km^{-1}; 22 February 2011 $PGA_{7.5}$ ranged 0.10 to 0.58 g, with a maximum of 9.9 breaks km^{-1}; 13 June 2011 $PGA_{7.5}$ ranged 0.07 to 0.39 g, with a maximum of 9.3 breaks km^{-1}; and 23 December 2011 $PGA_{7.5}$ ranged 0.07 to 0.27 g, with a maximum of 3.2 breaks km^{-1}.

The extent of transient and permanent ground deformation induced by liquefaction depend upon local soil and groundwater conditions captured in the LRI. Figure 37 (bottom graph) shows AC breaks km^{-1} versus $PGA_{7.5}$ discriminating between different LRI zones, with logarithmic power curves fitted for each set of *LRI* zone data. Despite the scatter evident in the data, for a given $PGA_{7.5}$ value breaks per km are in general higher in zones with lower liquefaction resistance or LRI, with a consistent trend in the relationship as a function of *LRI*.

It is important to emphasize that further studies using more rigorous methodology are currently under way; it is anticipated that this more rigorous evaluations will produce improved damage correlations based on *LRI.*



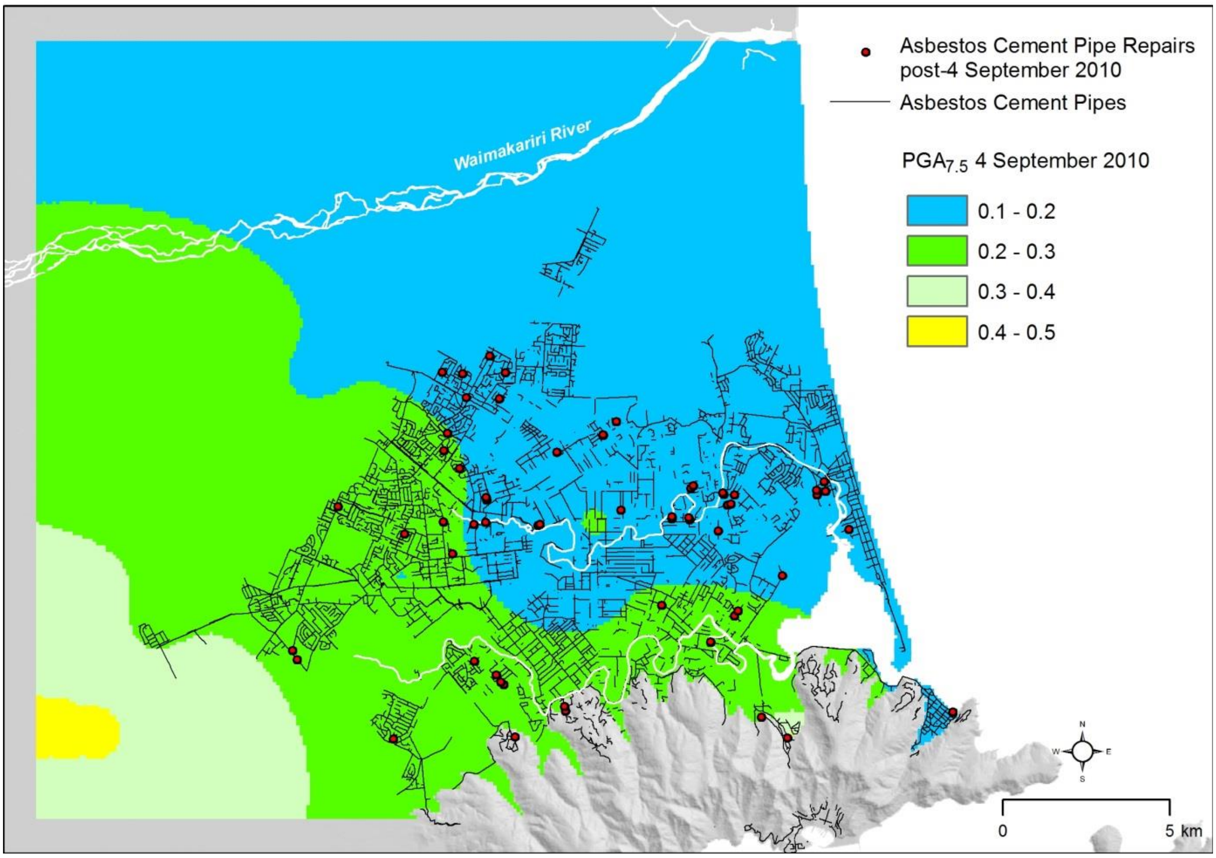
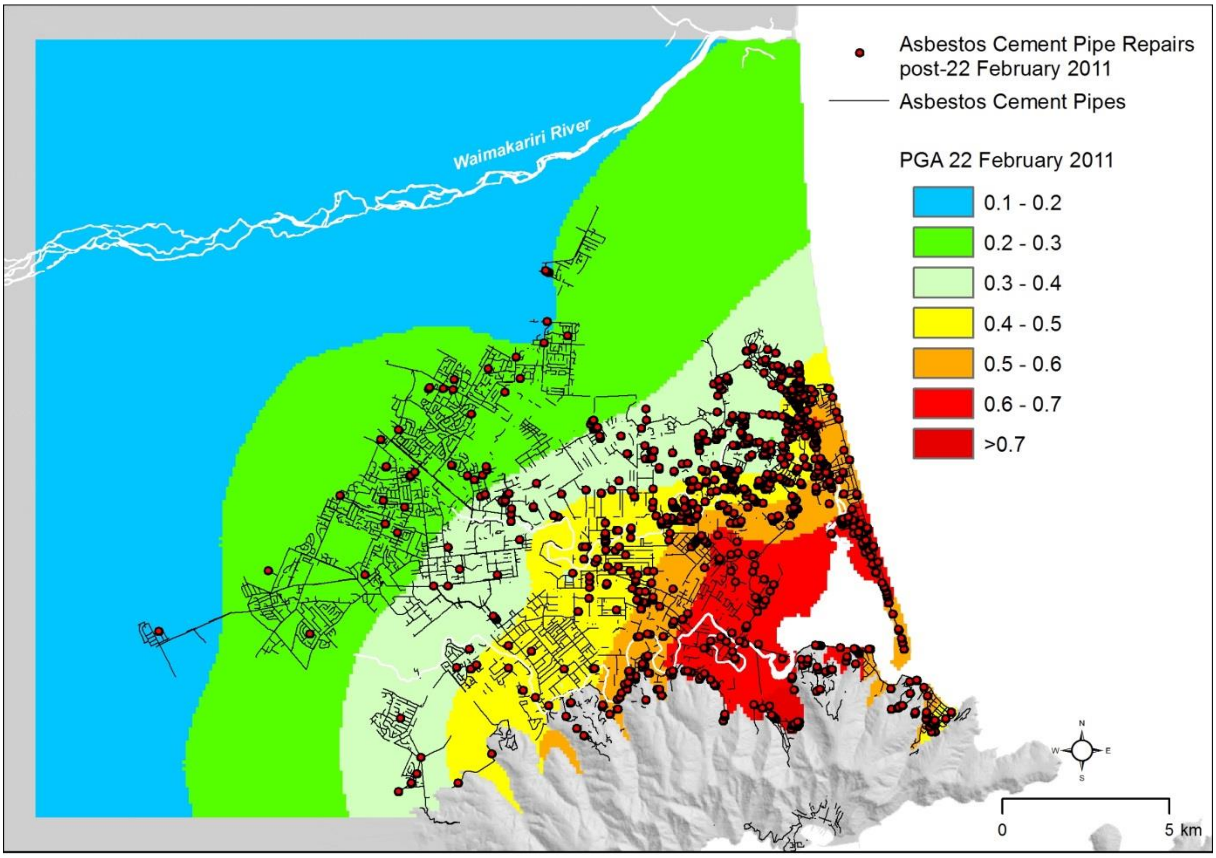


Figure 33. Top: Peak Ground Accelerations (g) across Christchurch City on 4 September 2010, with subsequent AC pipe repair locations shown. Bottom: Correction for $PGA_{7.5}$.



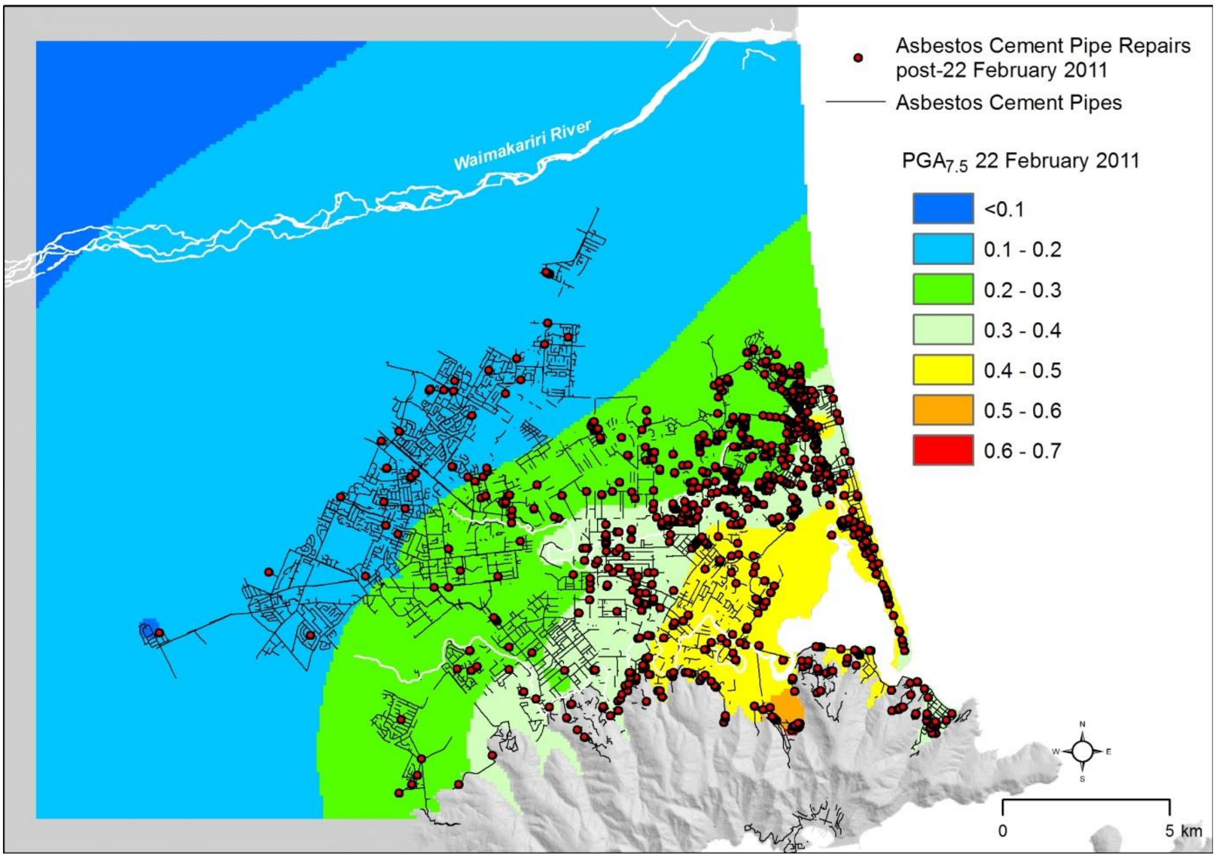
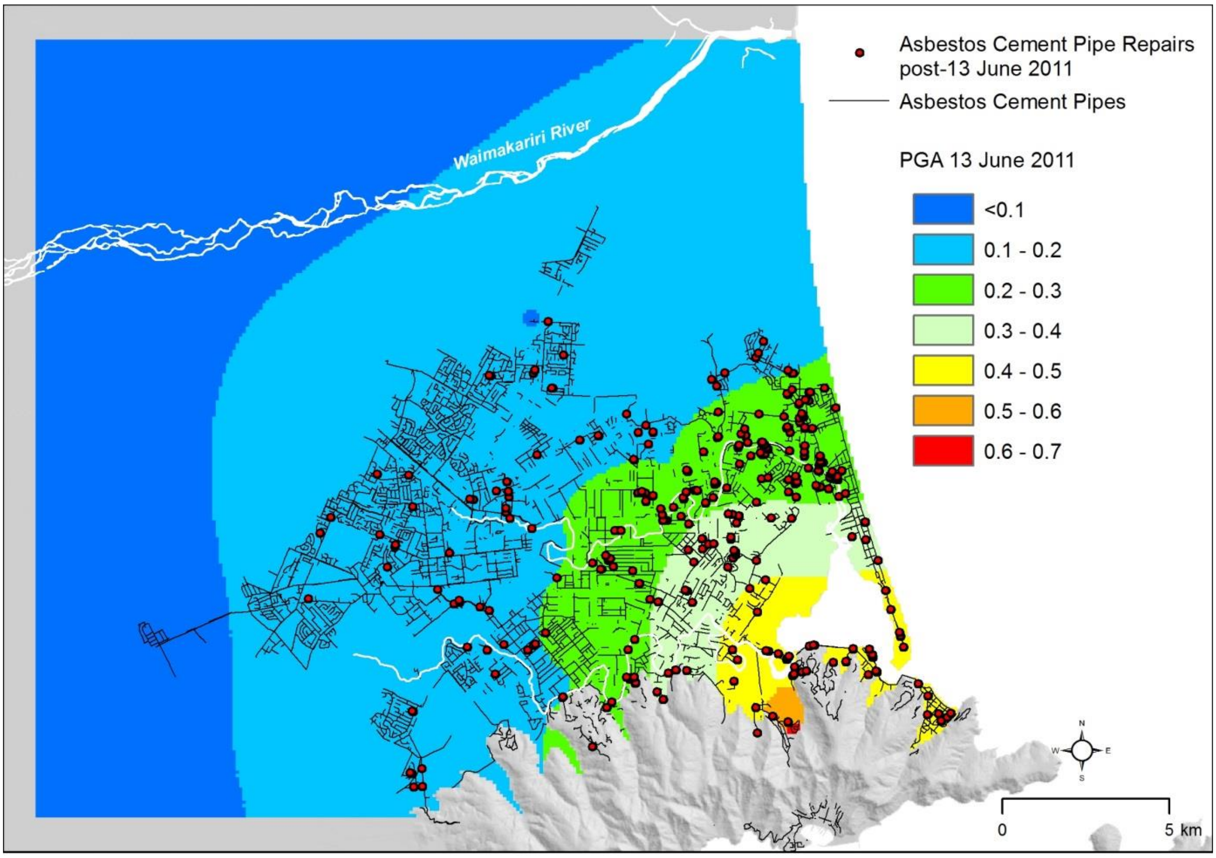


Figure 34. Top: Peak Ground Accelerations (g) across Christchurch City on 22 February 2011, with subsequent AC pipe repair locations shown. Bottom: Correction for $PGA_{7.5}$.



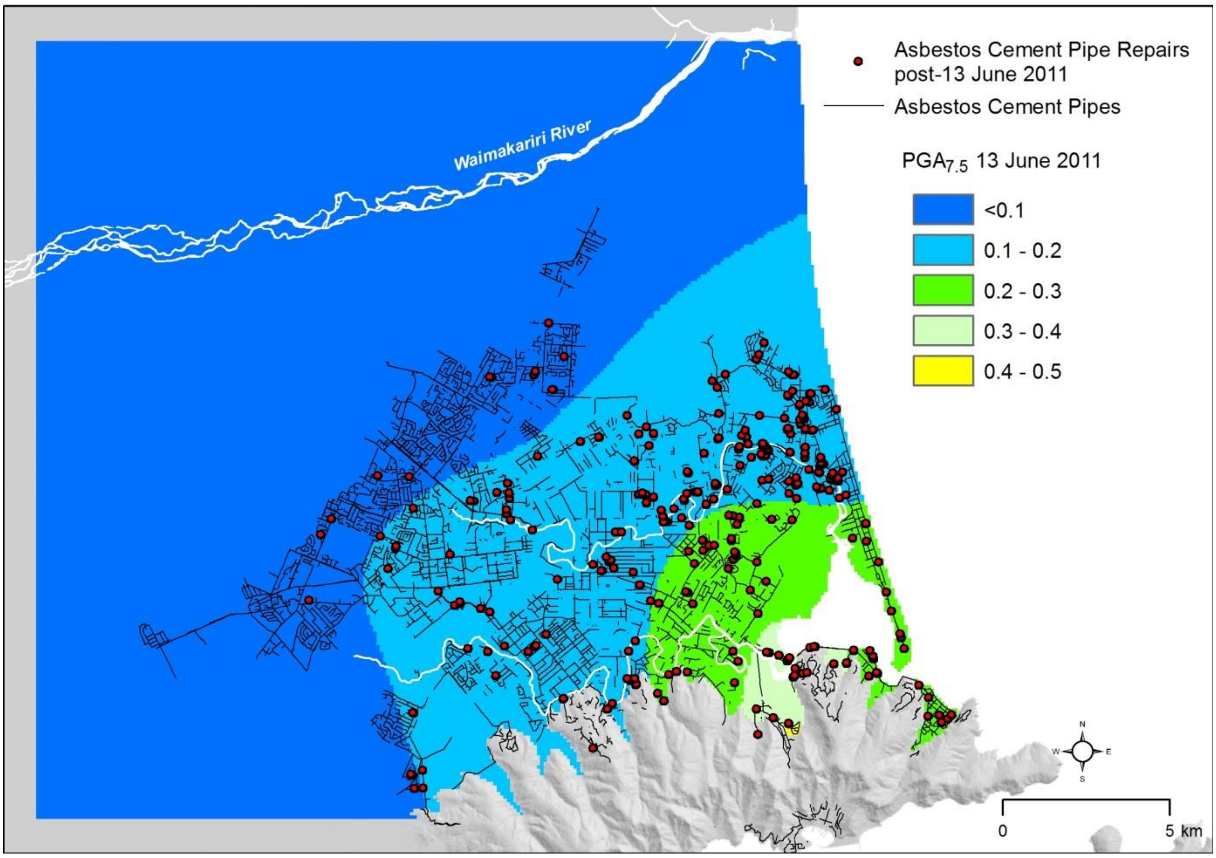


Figure 35. Top: Peak Ground Accelerations (g) across Christchurch City on 13 June 2011, with subsequent AC pipe repair locations shown. Bottom: Correction for $PGA_{7.5}$.

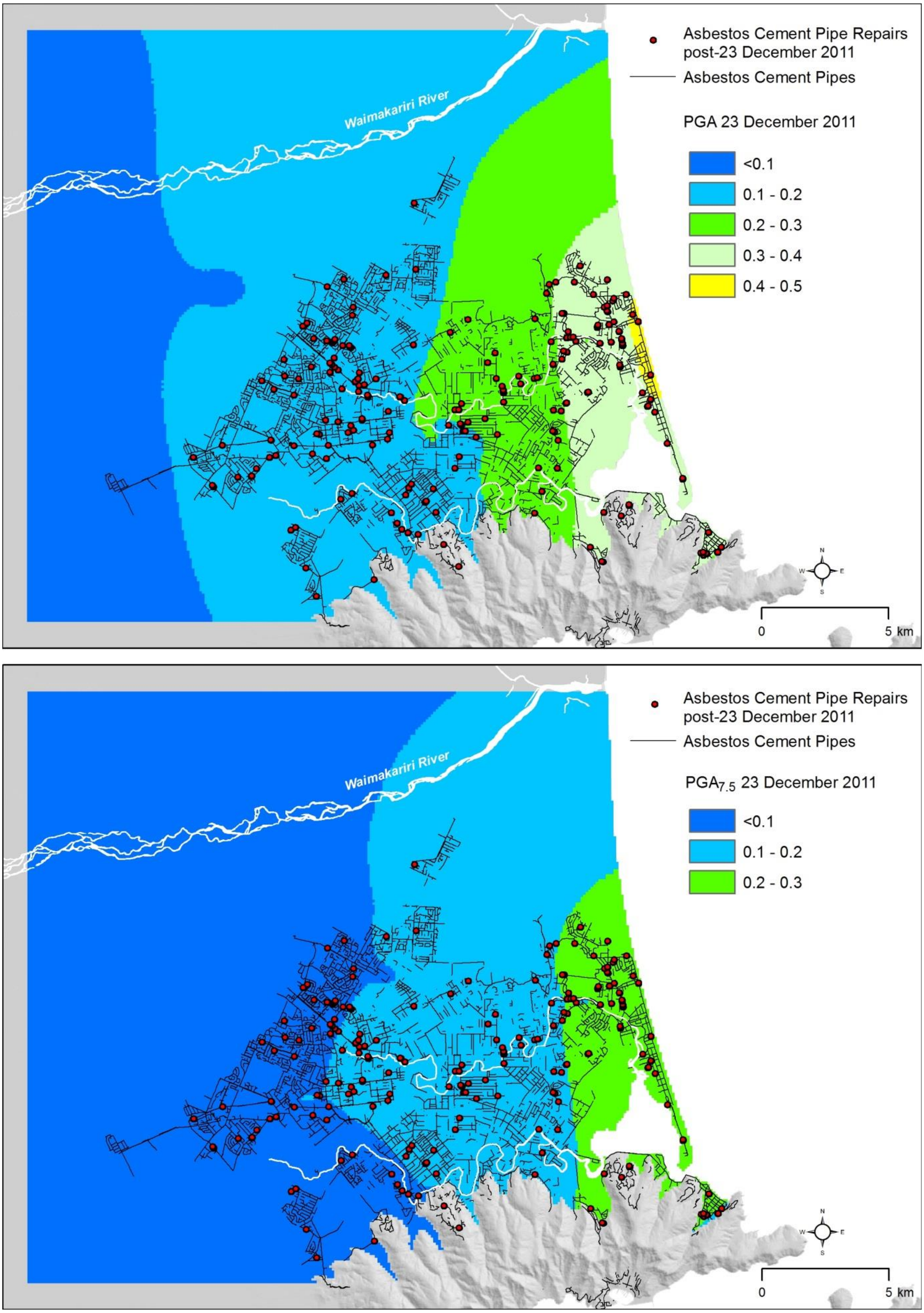


Figure 36. Top: Peak Ground Accelerations (g) across Christchurch City on 23 December 2011, with subsequent AC pipe repair locations shown. Bottom: Correction for PGA7.5.

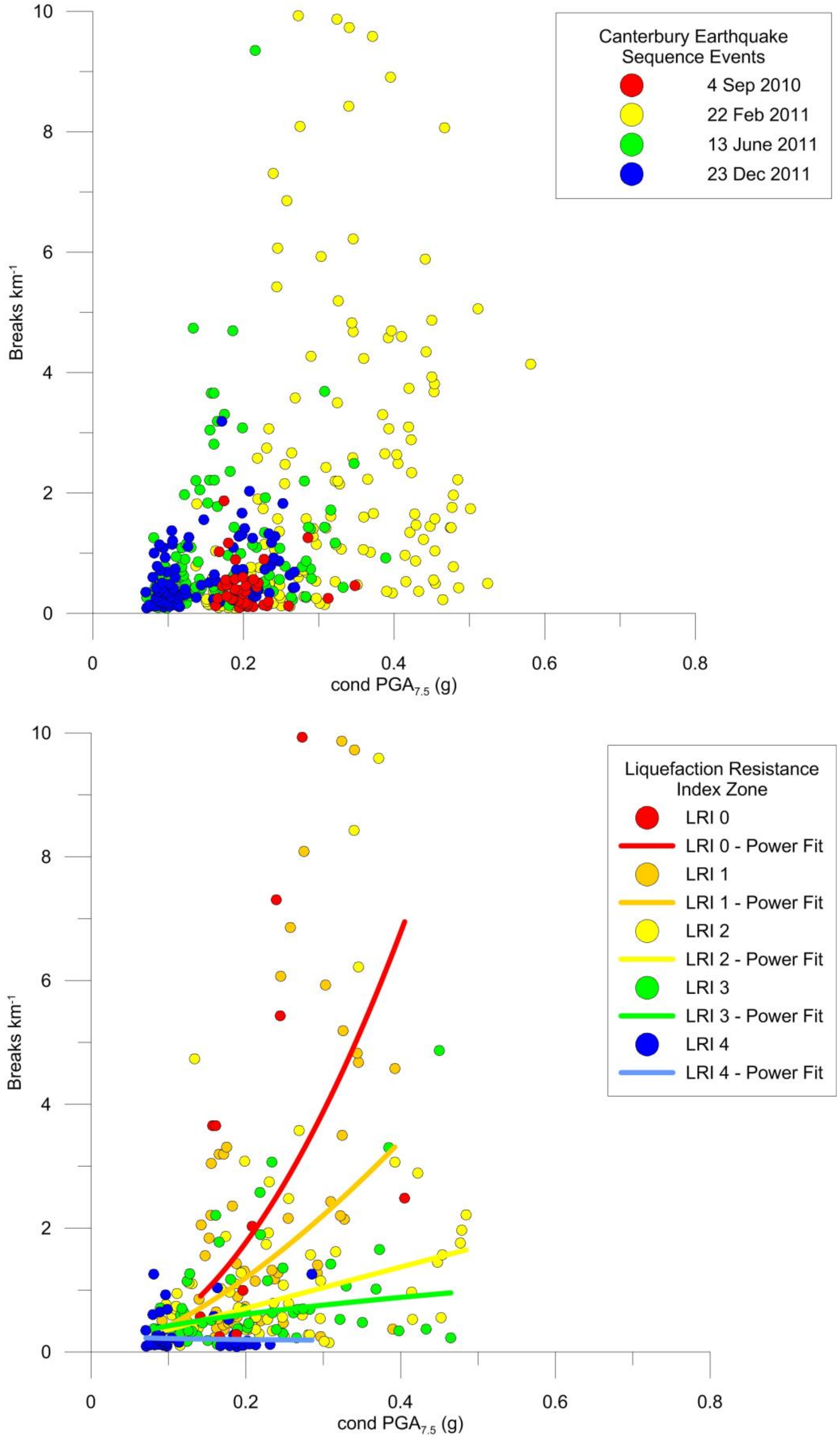


Figure 37. $PGA_{7.5}$ versus breaks km^{-1} for AC pipes across Christchurch City. Top: Data plotted according to CES events. Bottom: Data plotted according to LRI Zone, with power curves fitted. Power fit equations are presented in Table 4. Note that data points outside of the LRI Zones are excluded.

Table 4. Power fit equations for curves presented in Figure 37**Error! Reference source not found.**. BR=Break Rate.

LRI Zone	Power Fit Equation
0	$\ln(BR) = 1.937556912 \times \ln(PGA_{7.5}) + 3.689079239$
1	$\ln(BR) = 1.505203382 \times \ln(PGA_{7.5}) + 2.604857021$
2	$\ln(BR) = 0.9622850792 \times \ln(PGA_{7.5}) + 1.197952162$
3	$\ln(BR) = 0.5311704354 \times \ln(PGA_{7.5}) + 0.3612575905$
4	$\ln(BR) = -0.1205609288 \times \ln(PGA_{7.5}) - 1.797476719$

3.3 Lessons from the Canterbury Earthquake Sequence

3.3.1 Performance of potable water system in CES

The water network repair time lines (Figure 12) illustrate clearly the magnitude of post-earthquake repair response in the face of widespread damage, particularly after 22 February 2011. These data support the general picture of repair rates presented by O'Rourke et al. (2012), and provide further insight into the behaviour of pipes with different diameters. For those components of the network where comparisons are rigorous, there is a clear decrease in repair rates per km with increasing pipe diameter.

Using a larger, more accurate data set of pipe repair counts than used in previous studies (e.g. Cubrinovski et al. 2011, 2013; O'Rourke et al. 2013), this report provides an updated pipe material performance in terms of repairs km^{-1}. This largely supports previous findings. When pipe materials are further classified according to the LRI zone (Cubrinovski et al., 2011) in which they are located, we find that failure rates across all pipe materials are higher in zones with lower liquefaction resistance (*LRI*). Where comparisons of pipe diameters are valid, larger-diameter pipes perform better than those with smaller diameters, most likely due to increasing pipe wall thickness as well as the large number and potentially lower quality fittings/details in small diameter pipes. These performance data include repairs conducted after the 13 June and 23 December 2011 events that were not included in our initial analyses. The use of this long-term integrated data set in combination with the LRI demonstrates the utility of the LRI in understanding the geospatial distribution of water network failures in response to both transient and permanent ground deformation and their effects on the damage and performance of potable water pipes.

The increase in repair jobs after 22 February, 13 June and 23 December 2011 is an obvious response to these damaging events. However the on-going failure/repair rates in the months following each event is higher than that prior to the CES, which has implications for understanding post-event system resilience. It seems likely that the events of 4 September 2010 and 22 February, 13 June and 23 December 2011 initiated weaknesses that manifested or were detected later as failures requiring repairs. The increase in AC repair rates in the western suburbs (e.g. Ilam and Avonhead) following the 23 December 2011 earthquakes clearly suggests a cumulative effect of the earthquakes and progressive increases in damage to a point where repairs were eventually required. As shown in Figure 36, the need for AC repairs occurred in spite of the significantly smaller seismic demand ($PGA_{7.5}$) for these pipes imposed by the 2011 December earthquake clearly showing that the integrity of the pipes and this part of the network has deteriorated quite substantially over CES. Alternatively, the system may have been overloaded by the "new" state of the network placing larger serviceability demands on the still-operational components, as well as system pressure changes resulting from cessation and re-establishment of water flow during the repair process though the reasoning does not apply to the previously mentioned area in the western Christchurch. The combination of quake-stressed and damaged pipes and fluctuating pipe water pressures resulting from repairs to the system are likely to explain the higher on-going failure rate. On-going failures into 2013, with only very occasional minor aftershocks occurring, have also been anecdotally attributed by CCL staff to long-term ground settlement. These are clear indications that the sensitivity of the system to ground movements has increased substantially throughout CES.

It is difficult to establish definitively general patterns of pipe failure modes, due to relatively small samples sizes and significant numbers of records with no damage/repair information. However from the information that is available pipe failures are divided between damage to pipe body itself and pipe fittings. With the exception of GI, pipe fittings are comprised of materials different to that of the pipe to which they are attached. This does not seem to be problematic for our determinations of pipe performance, as illustrated by correlations between AC breaks per km and PGA (Figure 37), and these damage patterns tend to reflect the relative brittleness/ductility of the pipe materials regardless of fitting construction.

Despite the lack of comprehensive fault descriptions across all pipe types, the data that have been obtained provide insight into potential physical mechanisms underlying failure modes directly attributable to large-magnitude events. The occurrence of circumferential splits on pipes such as AC, CI and CLS reflect differential ground movements leading to failures in the body of the pipe itself. Conversely, there are a significant proportion of failures classified as bursts and longitudinal splits, and these failure mechanisms are associated with pipes being subjected to extreme pressures from within (see Ogawa et al., 1994). Since most Christchurch water pipes operate under low steady pressure (30-50 m; metres of head pressure, 1 m = 10 kPa), in order to create longitudinal crack failures the pressures from hydraulic transients must be very large (100 m; Pedro Lee, pers. comm.). Such extreme pressures will not only cause pipes to crack but is also likely responsible for fitting failures as shock waves propagate around the network. This suggests that high-pressure hydraulic transients can induce pipe failures in addition to the dominant influence of earthquake-induced differential land movements. If one considers only the data for failures of the pipe body presented in Appendix G and assumes that 50% of the reported *longitudinal splits* and 100% or all failures of the *blown pipe* type are attributed to hydraulic pressures than approximately 15% to 25% of the observed damage to the pipe body itself could be related to the high hydraulic pressures. Further research is needed to quantify the contribution of this particular mechanism to the overall failure rate.

The types of trench backfill appear to play a key role in pipe performance. In LRI Zones 0 and 1 the higher damage rates for HDPE and AC within native soil trench backfills suggests that these backfill materials are less protective of these pipes than are imported gravel and AP40 backfills. This is also the case for AC, PVC and CI pipes in LRI Zone 2. Conversely, GI pipe materials within native soils have similar to lower repair rates than for both imported gravel and AP40 for all LRI Zones. The use of AP40 was discontinued from ca. 2005 due to it being considered too abrasive for some pipe materials. The higher GI repair rates in AP40 backfill may reflect this abrasiveness on the widely-corroded GI network, whereas native sandy backfill materials appear to offer greater resilience to liquefaction impacts.

3.3.2 Water Network Database Management Issues

Prior to amalgamation of separate local boroughs into the CCC in 1990, the paper-based plans of pipe locations was already being digitised into electronic form able to be managed in a GIS. Due to this digitising process being perceived as a simple data entry task, non-experts were initially employed, leading to considerable variability in the quality of this spatial information between boroughs. For example, small sections of repair material (HDPE) were ascribed to the whole pipe length (GI or AC) when records were updated to a GIS. With amalgamation in 1990 these disparate datasets were merged into a new system still containing these legacy data quality issues, and discrepancies between pipes in the GIS and pipes in the field have been observed since by CCL contractors in the course of normal network maintenance. It was assumed that by the commencement of the CES >90% of the data were correct, with the mains pipes in particular having high enough accuracies to instil confidence in the GIS system. However, the CES has served to highlight errors in the submains data with the focus on using these spatial datasets to document system damage and prioritise repair works programmes. Such errors have proved problematic for efficient decision making based on criteria that incorporate pipe types (such as CCC, 2011). Updating the accuracy of the water network by SCIRT, and forwarding the updated data for CCC's own databases, has been an important task over the last 18 months. This suggests that, in principle, local authorities and managers of such systems need to be vigilant in keeping databases accurate and current.

A second issue is the pre-CES separation of the water network database within CCC into one for managing the physical infrastructure and another for asset management from a financial perspective. While this separation may have been considered necessary in a large organisation such as CCC, one consequence prior to and during the CES has been the potential alteration of one database without the other being simultaneously updated. There has been at least one instance where unique identification codes for individual pipes within the asset management database appear to have been altered for billing or other reasons in a unilateral decision, without the corresponding pipe records in the physical infrastructure database being updated. This situation is problematic within CCC, and also has implications for CCL which also use the databases in the course of their maintenance works.

A third key issue is the flow of information from CCL to CCC, and subsequently from CCL to SCIRT. Prior to the CES, repair information from CCL was sometimes incomplete and anecdotal, with questionable accuracy. Following 4 September 2010 the main focus of CCL and its contractors was to repair evident water system bursts, but there appears to have been little systemic data capture on repair locations and fault descriptions, as evidenced by the paucity of data for most pipe types in the period between 4 September 2010 and 22 February 2011 (see Figure 12 and Appendix C). Along with occasional field misidentification of pipe types, a significant problem in data collection was the use of hand-held Personal Digital Assistant (PDA) devices, the screens of which proved too small for users to accurately locate pipes and define repair locations. In the absence of detailed and quantitative information being collected in this period, personal knowledge and local observations by contractors were overwhelmingly relied upon by CCC staff to assist with pipe renewal decisions. Following 22 February 2011 there were concerted efforts by CCL to accurately capture data electronically, with increased use of high-resolution Global Positioning System (GPS) geo-location, and larger-screened tablet devices being used to enable accurate identification of pipes in the field. Issues of data quality were also addressed by CCL by commissioning an audit of repair data that identified as of early May 2011 approximately 29% of the CCL post-quake data were identified with confidence as being mains or submains (SKM, 2011); accordingly the damage/repair data bases were largely considered to be unreliable and therefore personal knowledge of system performance by contractors and CCL personnel was depended upon.

Despite the deficiencies in data capture and ensuring data quality, the resulting spatial database of post-earthquake water network repairs compiled through the CES is one of the most comprehensive ever collected. The widespread spatial coverage across Christchurch City has enabled the correlation of pipe repairs with PGA and ground performance. However, due to the significant lack of detailed pipeline damage information it is difficult to draw definitive patterns of failure modes even for those pipe types with widespread and numerous breaks (i.e. AC and GI), and this failure to record information on damage (whether pipe body or fitting, and nature of fault) has hampered in-depth engineering-science analysis of system performance. The failure to consistently record useful information through the CES is due to a range of reasons including: lack of prioritising such data recording by contractors in the field, either due to urgency of repairs and/or lack of education about the importance of data collection; appropriate field GPS/mobile GIS devices not being possessed by contractors; particularly after 22 February 2011, an influx of water supply contractors from around New Zealand who were not informed of the importance of collecting damage information.

Where information was collected by contractors in the field, a significant percentage of it was not useful for determining the nature of the fault. It was also difficult to identify the nature of the fault from repairs made, because the main repair methods (such as installation of repair clamps, or removing a pipe section and replacing with a length of PVC pipe) could be applied to a range of pipe faults. Terminology was also an issue, with inconsistent use of terms between contractors describing either damage or repairs. For example terminology describing pipe fittings was often based on the manufacturer's brand name, and different contractors used different terms based on their own experience with using various products – this was especially the case with contractors from outside of Christchurch. The establishment of a simple data dictionary to be installed on mobile GIS devices would greatly assist the collection of consistent information on failure modes.

The lack of detailed damage information through the CES is a legacy of pre-CES systems and processes. While the CES has served to highlight these problems, it has also accelerated the adoption of digital data collection to promote more seamless data transfer between organisations. Many utilities companies employ, as an integral of their normal business operations, the use of mobile GIS devices which automatically and remotely update central asset databases, and the relevant employees are trained in their use and understand the importance of seamless data collection for intelligent asset management. This combination of technology and education is essential for everyday operations, and becomes even more important in a disaster context where asset management systems should be able to receive voluminous data in a short time frame to facilitate decision-making in emergency response and recovery. The experience in Christchurch City has served to highlight many of these issues which will be present in territorial authorities across New Zealand and internationally.

3.3.3 Potable water system resilience

The good performance of PE, PVC and MPVC pipes across Christchurch City reflects the resilience of these materials in the face of repeated earthquakes causing widespread liquefaction and lateral spreading and consequent large ground deformation, compared to the poor performance of more brittle pipes such as AC and GI. This trend towards use of PE and PVC started in earnest in the 1990s with the development of new subdivisions on the city margins. The instigation of an accelerated renewals programme through the Christchurch rebuild means this trend of installing resilient materials will continue, and the emerging new potable water network can be expected to be significantly more resilient to earthquake impacts than prior to the CES. Clearly the choice of appropriate pipe materials and pipeline details does make a significant impact on the performance of this critical lifeline. However, there is also clear evidence that pipe materials alone will not guarantee excellent ort acceptable performance. Fittings and other important components of the network must be brought up to acceptable standards to ensure good performance and service of the system.

Since early 2013 SCIRT has conducted a comprehensive programme of leak detection to assess whether system leakage has returned to pre-CES levels. Initial findings from this programme show that mains pipes are in general stable, with leakage rates approximating those observed prior to the CES. While this is a clear measure of success, the programme has also shown that approximately 75% of observed leaks are occurring at small connections to and within the submains/crossovers components of the network. This suggests that further system resilience can be achieved through improved design of connections and greater attention to details.

Recently, a private initiative has launched in Christchurch called Sensing City (see http://sensingcity.org/). To quote from Sensing City's website: "The Sensing City concept positions Christchurch as a world leading smart city by incorporating an integrated network of digital sensors into the physical infrastructure (utilities and buildings) of the Christchurch CBD that generate real time, granular data for multiple uses and benefits". Sensing City is in discussion with various stakeholders at CCC and the Canterbury Earthquake Recovery Authority (CERA), and has the support of senior government ministers in its implementation. The installation of a digital sensor network into the potable water system – the incorporation of a "soft data infrastructure" into the "hard infrastructure" of water utilities, could lead to significant efficiencies in normal water management operations, understanding system functioning in real-time, and provide more immediate and useful feedback in the wake of natural disasters. While there are technological difficulties to be addressed with such sensing/data networks, this is currently work in progress. The Sensing City approach provides a unique avenue for territorial authorities, recovery agencies, the private sector and research organisations to collaborate on initiatives that improve urban infrastructure management and resilience in the face of future seismic risk.

3.3.4 Preliminary findings

Key findings from this study on the potable water network can be summarised as follows:

- Modern water pipe materials and more flexible pipelines that can better accommodate ground deformation including relatively large permanent displacements, such as PVC/MPVC and MDPE80 and HDPE, performed significantly better through the CES than older materials and more brittle pipelines such as AC and GI, as determined by breaks km^{-1}. Areas where PVC and PE pipelines are installed are therefore inherently more resilient to seismic impacts than older parts of networks with a legacy of vulnerable components.
- For all pipe materials, there is clear link between liquefaction severity and damage rate to the pipeline: an increasing damage rate is observed with increasing liquefaction severity. Note that most of the damage to buried pipelines is induced by excessive ground deformation and permanent ground displacements (vertical=settlement; lateral; shearing,

longitudinal movement; combined=angular distortion). Such ground deformation and displacements are principal consequences of liquefaction, and hence the observed (and expected) strong correlation between liquefaction severity and pipeline damage. PGA and similar ground motion intensity measures (PGV in particular) provide an alternative/additional set of measures for correlating the damage to buried pipes caused by strong earthquakes, and they are particularly useful in areas where no ground failure due to liquefaction was observed. The approach taken here was to correlate the pipeline damage to *LRI* (Liquefaction Resistance Index, newly developed parameter in Cubrinovski et al., 2011) which represents a direct measure for the soil resistance to liquefaction while accounting for the seismic demand through PGA. Key quality of the adopted approach is that it provides a general methodology that in conjunction with conventional methods for liquefaction evaluation can be applied elsewhere in New Zealand and internationally. Needless to say, it can be easily incorporated into risk modelling software such as RiskScape.

- Preliminary correlations between pipeline damage (breaks km^{-1}), liquefaction resistance (*LRI*) and seismic demand (*PGA*) have been developed for AC pipes, as an example. Such correlations can be directly used in the design and assessment of pipes in seismic regions both for liquefiable and non-liquefiable soils.
- Modes of pipe failure are divided between damage to the pipes themselves, and damage to attached fittings. The field data on pipe damage collected in Christchurch is not sufficiently comprehensive or detailed to provide definitive patterns of damage across the network, however some clear patterns are emerging as follows: (a) There are consistent patterns of damage to the major pipe materials regardless of failure mode (e.g. AC pipes performed more poorly than did PVC or PE pipes, regardless of the specific nature of earthquake damage); (b) 85% to 95% of the damage to HDPE and MDPE pipelines was due to fitting damage/failure, with very little damage associated with failure/damage of the pipe body itself; (c) conversely, for AC pipes, about 60% of the damage was in the pipe damage category and the remaining 40% in the fitting damage category.
- The effects of backfill materials on the pipeline damage were also investigated using the *LRI* methodology as a basis. It was found that AP40 backfills significantly improved the performance (reduced repairs per km) for HDPE and AC pipelines as compared to backfills from native soils. On the other hand, no such improvement was observed for the GI pipes.
- Comprehensive and accurate GIS databases are essential for disaster response/recovery management. However the legacy of geospatial database creation can lead to inaccuracies in spatial information and associated non-spatial data, which is problematic when these data are relied upon for post-disaster decision-making around infrastructure repairs and renewals.
- Utilities companies need to ensure electronic field data capture, using accurate spatial databases and appropriate field devices, as a normal part of daily operations. The development of a consistent and agreed-upon "data dictionary" for use by utilities companies such as CCL and their contractors would streamline data capture and provide more useful information for day-to-day operations and in post-disaster analysis.
- There needs to be a geospatial data champion within each water utility organisation (e.g. CCC, CCL) to ensure data standards are maintained, and any separate data systems within an organisation are linked to ensure simultaneous updating. Considering the multiple agencies concerned in data collection and asset management, such champions should ensure that data flow and integration with other agencies is as seamless as possible.

3.4 On-going and future research

The next steps in analysis of the Christchurch potable water system are as follows:

- The developed methodology for pipeline damage assessment based on *LRI* and seismic demand (*PGA* or *PGV*) will be implemented more rigorously (with exact *LRI* values used for a given pipe, rather than estimates based on 1km^2 mesh).
- Using the updated methodology, empirical correlations and analytical models (damage predictors) will be established for pipelines of different materials (AC, GI, CI, CLS, HDPE, MDPE80 and PVC) for soils with different levels of liquefaction resistance (*LRI*) and various levels of seismic demand (expressed in terms of *PGA* and *PGV*). This will provide: (a) a complete methodology for assessment of damage to potable water pipelines (for Christchurch, but also transferable elsewhere in New Zealand and internationally); (b) basis for development of fragility curves for incorporation into seismic risk assessment methodologies such the RiskScape model (see http://www.riskscape.org.nz/), to enable the lessons from Christchurch to inform seismic hazard scenarios across New Zealand.
- Further update, scrutiny and analysis of the damage data on the potable water network and refinement of preliminary findings.

4.0 Waste Water System

4.1 Introduction

Following the 22 February 2011 Christchurch Earthquake an extensive Closed Circuit Television (CCTV) inspection programme was commenced to identify earthquake damage to the network of more than 1,600 km of gravity wastewater and 900 km of gravity storm water pipes, using the New Zealand Pipe Inspection Manual as a methodology (Water NZ, 2011) to define the nature and severity of defects. The cost of collecting CCTV data on all gravity pipes was estimated to be in the order of NZ$125 million. Due to the extensive network damage and despite having at least 20 CCTV crews in the field (equating to around half of New Zealand's specialist CCTV field resource), the estimated time required to complete CCTV survey of damaged pipes across Christchurch City was more than four years. The availability of CCTV data thus became a critical constraint to the rebuild. The difficulty in assessing the extent of wastewater damage for a range of rebuild priorities led to the development of Pipe Damage Assessment (PDA) Tool to provide desktop assessment of both waste water and storm water pipe condition through the CES (Kinley et al., 2013). The objective was to speed up the rebuild process by providing estimates of damage based on a range of inputs including CCTV observations from across the city, which were used as a representative sample of the pipe condition. The correlation of CCTV damage data with other local indicators of damage was used to estimate damage at locations unsurveyed using CCTV. Other damage indicators used were pipe material, depth, diameter and flow direction, proximity to water courses, road condition data, city subcatchment and LRI Zones (Cubrinovski et al., 2011). By using a multiple-parameter approach the PDA Tool achieved up to 95% accuracy, compared to up to 60% accuracy for a single parameter approach. Outputs were successfully applied to the design of rebuild works, scoping and budgeting, and for prioritisation and estimating (Kinley et al., 2013). See Appendix J for more detail on PDA Tool development and application.

Current work being undertaken at SCIRT includes the development of a detailed 3-dimensional model of the waste water and storm water system informed by detailed surveys conducted across the entire network. These models are being used for hydraulic analyses and scenarios of system functioning in response to potential future earthquakes and demographic changes in Christchurch.

Presented here is a preliminary analysis of the waste water network through the CES, based on repair data as opposed to CCTV interpretations. The waste water network across Christchurch City is deeper than the potable water system and is mostly unpressurised, and therefore there is a still-emerging picture of performance. Despite this partial dataset, trends in system performance are able to be identified. Also presented here are the results of liquefaction impacts on manholes, critical nodes within the wastewater system.

4.2 System characteristics and development

As with the potable water network, the spatial variation in waste water pipe types across Christchurch City reflects the historical development of the system. When mapped by decade of installation the nearly concentric expansion of the Christchurch urban area is evident (Figure 38), and the age of pipes is closely associated with the pipe materials used (Figure 39). By the commencement of the CES (4 September 2010), >1700 km (91%) of the network was comprised of gravity pipes, of which 45% were comprised of concrete (CONC), 22% comprised of earthenware (EW), 18%

comprised of UPVC and 8% comprised of AC pipes (Table 5). The pressurised components of the system comprise 8% of the total network length, with the dominant material being UPVC (33% of pressure system) followed by AC (23%), CONC (16%) and MPVC (13%).

Table 5. Summary of Christchurch City and Lyttelton Harbour waste water network pipe types and materials as of 4 September 2010.

Pipe Material	**Gravity**		**Pressure**		**Other**		**Total km**	**% of Total Network**
	km	**% of Gravity**	**km**	**% of Pressure**	**km**	**% of Other**		
CONC	768.494	45	23.748	16	3.550	14	795.792	42
EW	380.811	22	0.011	0	0.132	1	380.955	20
UPVC	310.297	18	48.976	33	1.434	6	360.708	19
AC	138.260	8	33.723	23	0.647	3	172.630	9
Other	43.183	3	4.248	3	15.050	59	62.476	3
PVC	44.924	3	4.891	3	0.678	3	50.493	3
MPVC	3.463	<1	18.840	13	0.0005	<1	22.304	1
HDPE	15.323	1	3.445	2	3.276	13	22.043	1
CI	14.582	1	4.842	3	0.686	3	20.110	1
MDPE80	1.401	<1	5.389	4	0.124	<1	6.914	<1
BB	5.948	<1	-	-	-	-	5.948	<1
Total (% of network)	**1726.686 (91)**		**148.114 (8)**		**25.573 (1)**		**1900.373**	

As described by Wilson (1989), the establishment of the waste water system in Christchurch City from the 1870s entailed the provision of relatively steep pipe grades in the gravity system to overcome Christchurch's flat topography. The original plans were to have separate systems for waste water and storm water, with the city's sewage to be directed to and treated at Bromley, and all storm water to be discharged to the city's rivers and the Avon/Heathcote Estuary. Original plans were also to enable the infiltration of groundwater (as oppose to storm water) into the waste water pipes, but upon system construction this was reconsidered because excessive groundwater infiltration might incapacitate pump stations. Despite early and on-going attempts to prevent the waste water system from acting as a drain of Christchurch City's groundwater, the "leakiness" of Christchurch's waste water system has long been recognised.

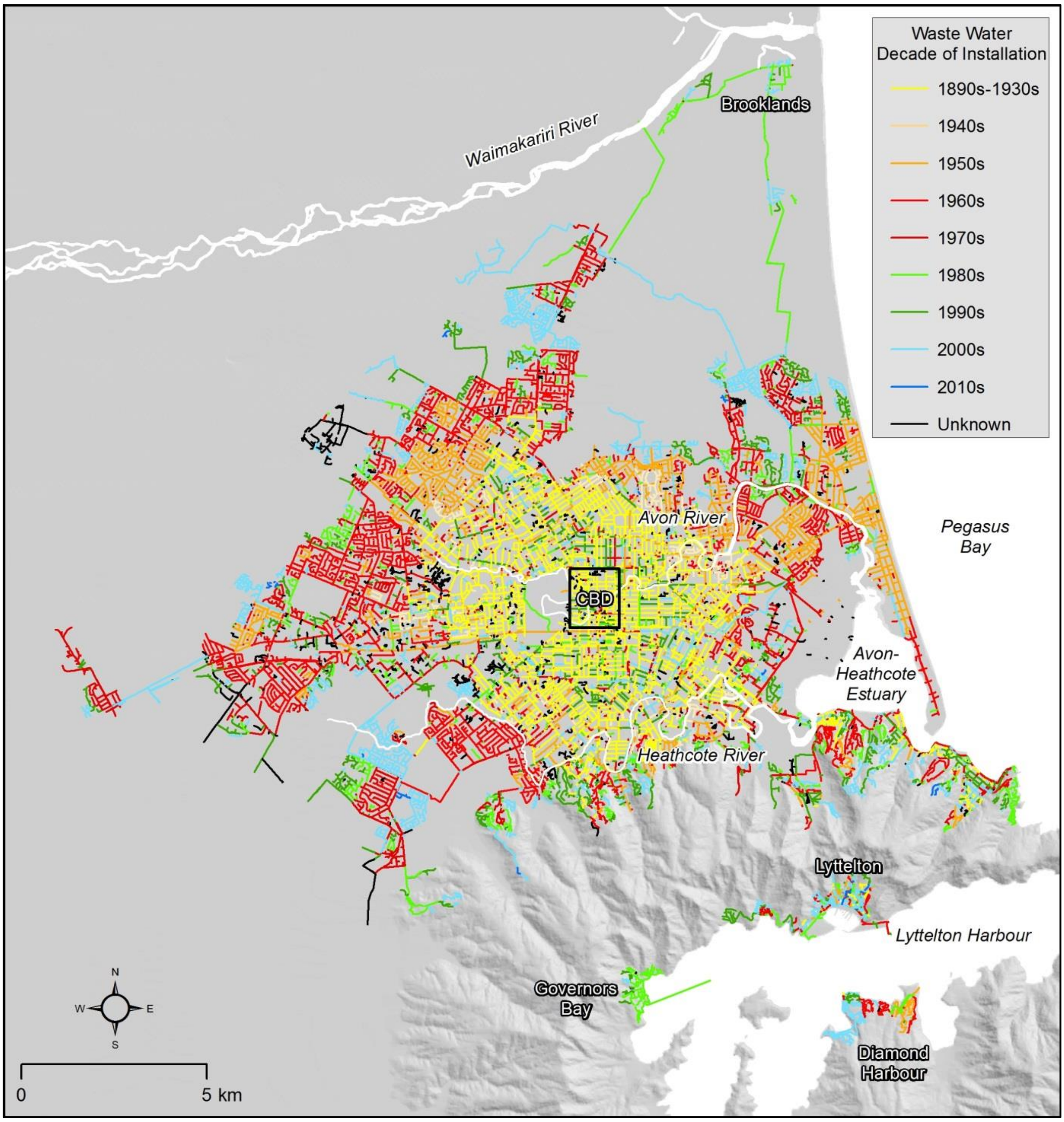


Figure 38. Christchurch City and Lyttelton Harbour waste water network mapped according to decade of installation.

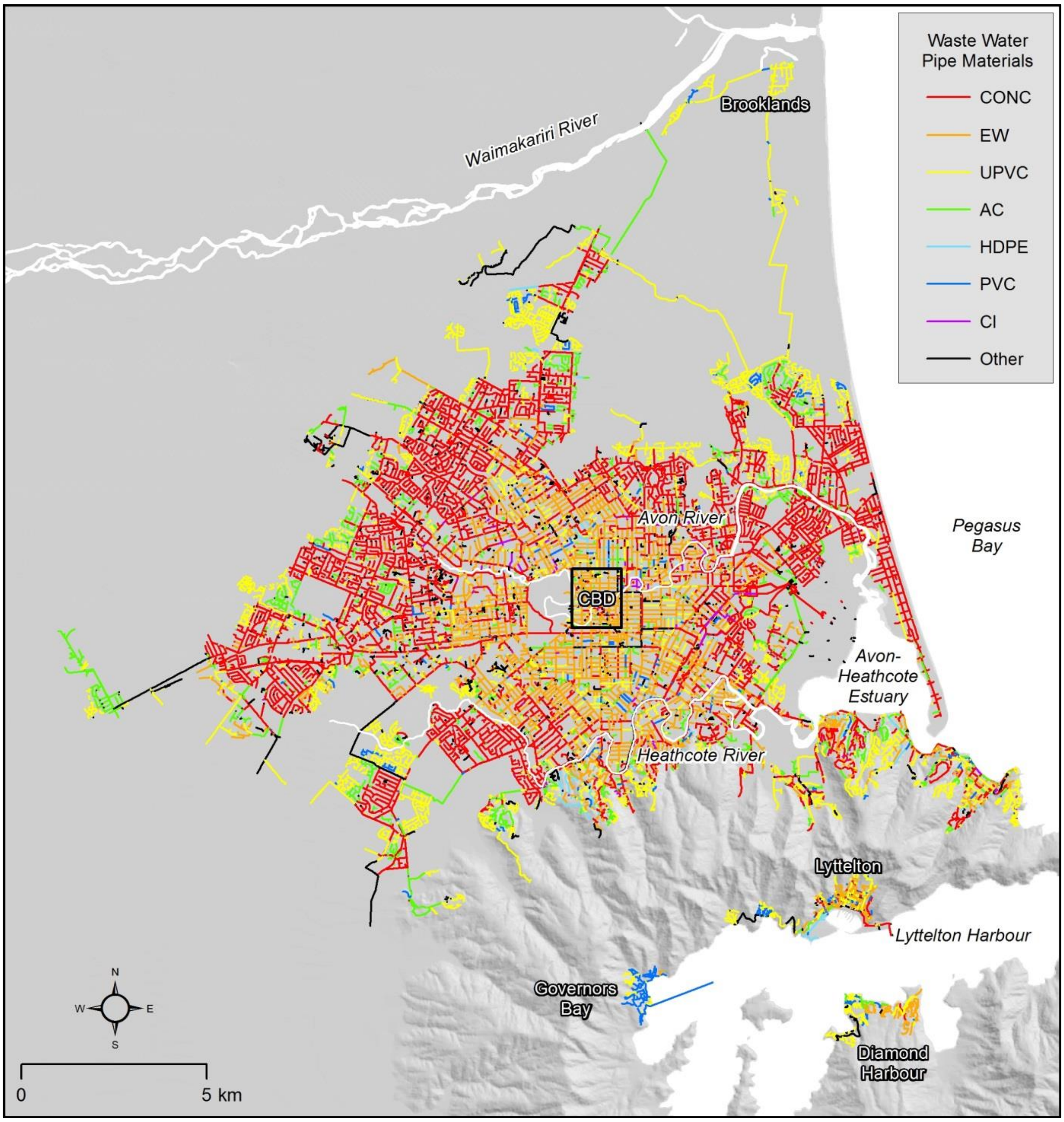


Figure 39. Christchurch City and Lyttelton Harbour waste water network mapped according to pipe materials as of 4 September 2010.

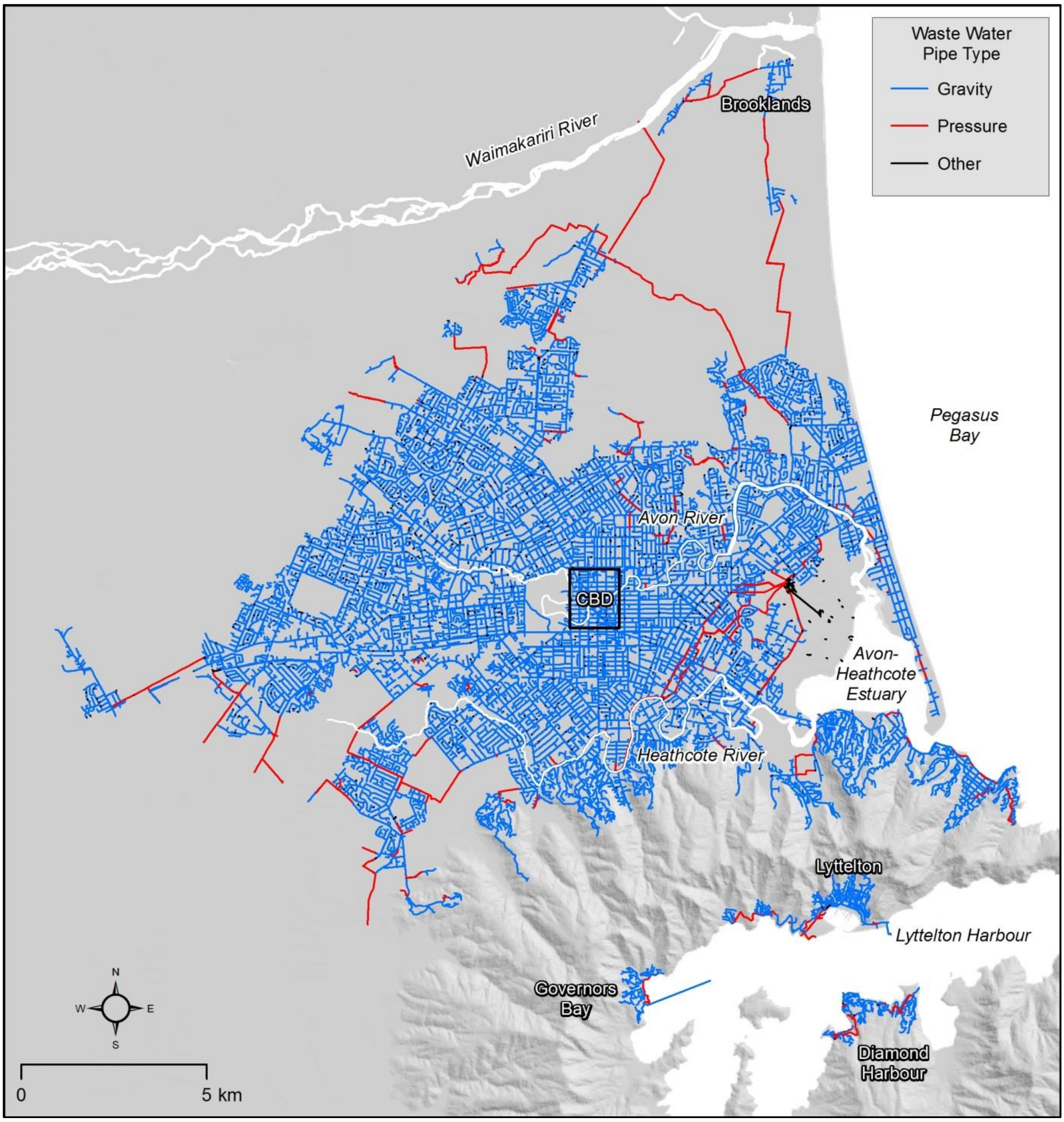


Figure 40. Christchurch City and Lyttelton Harbour waste water network mapped according to pipe type.

4.2 Analysis

4.2.1 Network Data

The waste water network data used in this analysis were obtained from SCIRT in June 2013. The SCIRT data were sourced originally from CCC. There is on-going updating of the database as the rebuild programme proceeds. For this analysis pipe information was sorted to exclude any pipes installed after 4 September 2010.

4.2.2 Pipe damage assessment - repair counts

Pipe repair count data used here were obtained from SCIRT's GIS team on 11 March 2013, and represent the most accurate picture of the system's spatial distribution and specifications up to this point. The data were in the form of a polyline shapefile, with number of repairs per pipe for the period 5 September 2010 to 5 June 2013 ascribed to each pipe record (see Figure 41). These repair count data represent <5% (~80 km) of total system length.

4.2.3 Pipe damage assessment - repair counts and Liquefaction Resistance Index

Pipe material performance according to LRI was determined. To avoid difficulties where an individual pipe traversed the boundary between two LRI zones, the mid-point of each pipe was defined (half-way along pipes of any length) and intersected with the LRI map (see Figure 42). For each major network pipe material within each LRI zone numbers of repaired pipes, affected lengths, total repairs and repairs per km were calculated for each diameter class.

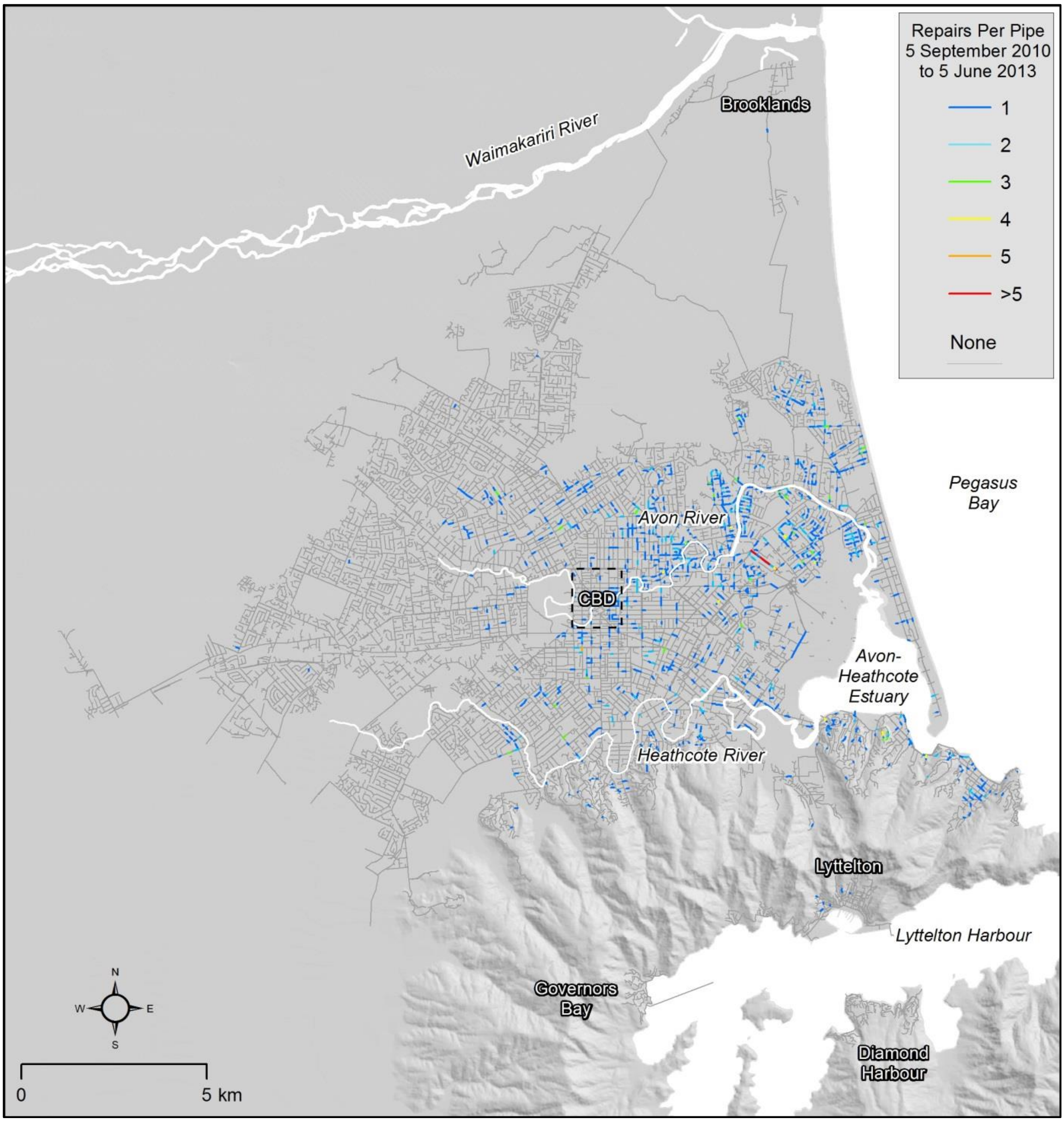


Figure 41. Numbers of repairs per pipe in Christchurch City and Lyttelton Harbour over the period 5 September 2010 to 5 June 2013.

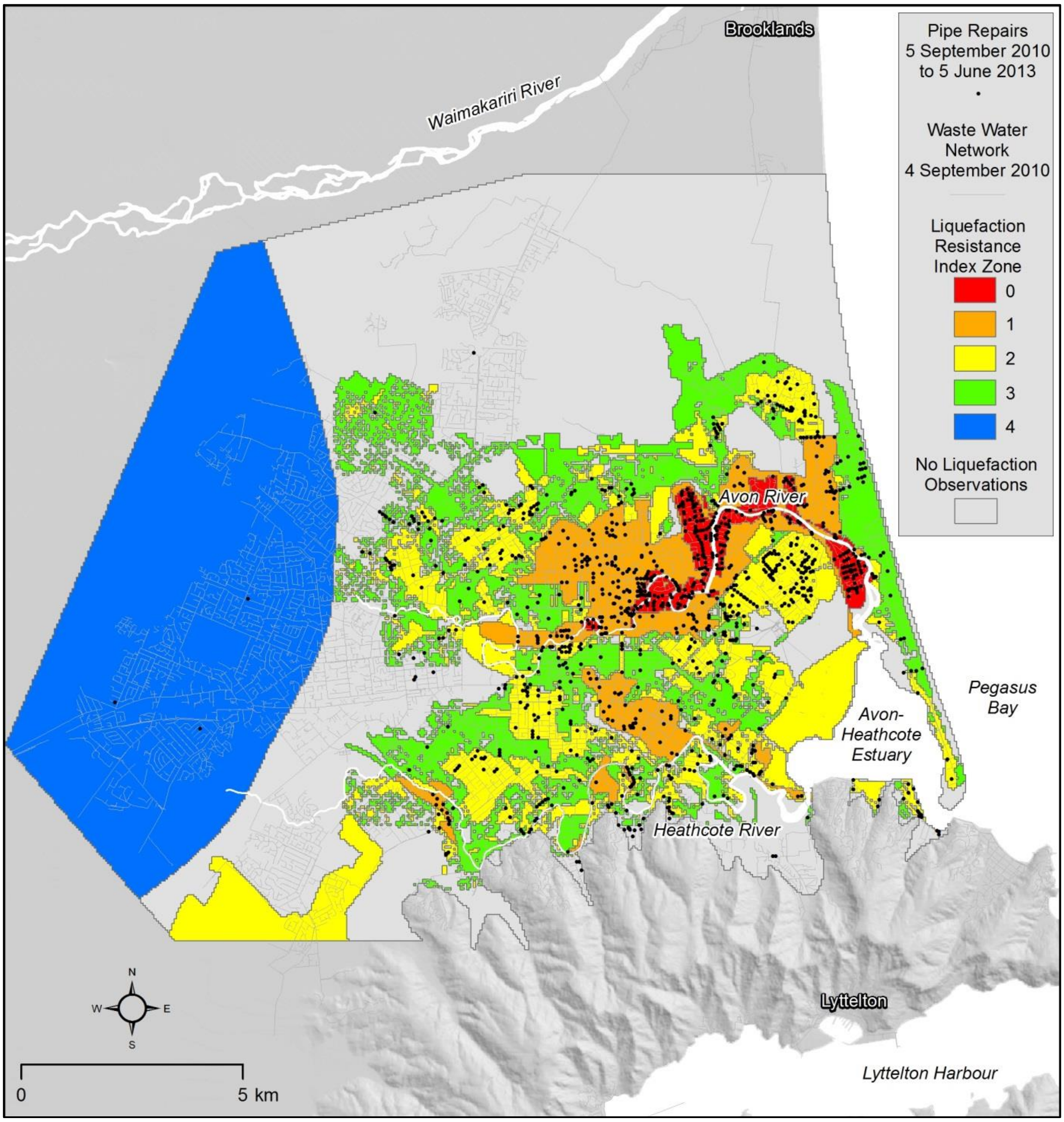


Figure 42. Locations of repaired waste water pipe midpoints within the LRI analysis area, and LRI zones. See Table 2 for LRI Zone ground deformations.

4.3 Results

Pipe Repair Rates According to Material and Liquefaction Resistance Index Zone

Repair records to date represent only a small percentage of the network that will ultimately be repaired and replaced, and therefore the calculated repairs rates must be considered preliminary. Affected lengths for CONC and EW are ~43 km and ~35 km, respectively. Affected lengths for AC and UPVC are ~6 km and ~3 km, respectively (Figure 43). The remainder of affected lengths for the repaired pipes of other materials are all <1 km in length. EW pipes had the highest repair rate of 1.5 repairs per km followed by CONC (1.0 repairs per km) and AC (0.7 repairs per km).

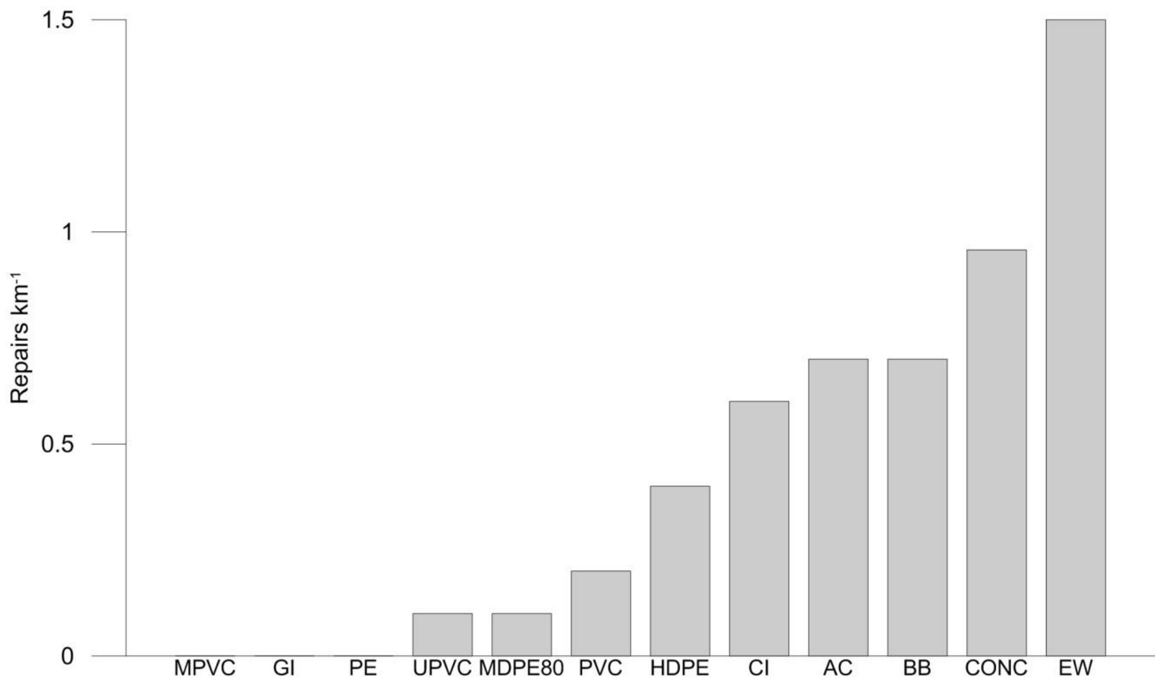


Figure 43. Summary repair data for waste water pipe materials. Data cover the period 5 September 2010 to 5 June 2013.

A subset of the water network repair data within the LRI analysis area (Cubrinovski et al., 2011; 2013) shows that for most pipe material types there is a consistent decrease in repair rate from LRI Zone 0 to LRI 3 (Figure 44). There is a clear link between LRI and repair rate for all pipe materials. Within LRI Zones 0-2, EW had the highest repair rate followed by CONC and AC.

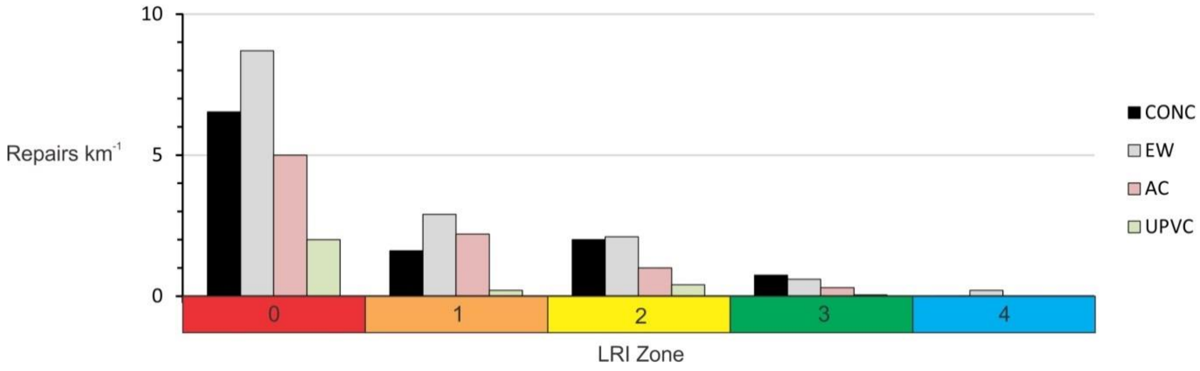


Figure 44. Summary repair data for the four most spatially extensive waste water pipe materials (Concrete, Earthenware, Asbestos Cement and Plasticised Polyvinyl Chloride) within Liquefaction Resistance Index Zones . Data cover the period 5 September 2010 to 5 June 2013.

Analysis and design of manholes in liquefiable soils

A detailed treatment of the behaviour of waste water system manholes through the CES is presented in Appendix K. Motivation for this research arose from discussions with SCIRT staff, which identified these critical system components as requiring more research, particularly in manhole responses to potential liquefaction.

The behaviour of manholes in liquefiable soils is highly variable and there are many factors that control the magnitudes of relative displacements. Some key findings are:

- The vulnerability of the system is highly variable due to the development of technologies and construction methods over time. Liquefaction severity is also highly variable over large areas.
- Two dominant manhole types (square cast in-situ and circular pre-cast) were the focus of the investigation. The key difference between these two types is the weight (square manholes being approximately 3 times heavier than circular manholes) which was shown in parametric analyses to be an important parameter controlling manhole uplift in liquefaction areas.
- Manholes assigned with relative displacement and observed liquefaction severity data were analysed. A clear link between liquefaction severity and observed relative displacements was found, with manholes showing less relative displacement in areas of no liquefaction (up to 63%) and more in areas of high liquefaction severity (up to 57%), as expected.
- The depth of manhole embedment appears to be an important parameter affecting the relative displacements of manholes. There was a clear transition between relative displacement severities at approximately 3.0 m embedment depth. Shallow manholes performed better with less relative displacements observed. Very deep manholes had high levels of observed relative displacement. Parametric analyses confirmed these observations.
- Parametric analyses demonstrated that several parameters influence the rate and maximum uplift of manholes. The embedment depth and water table depth are two of these key parameters. Penetration resistance (evaluated by CPT) and liquefied layer thickness are also significant parameters. Uplift of manholes was found to significantly increase for CPT resistance of the critical layer of less than 5 MPa.

4.4 On-going and future research

The next steps in analysis of the Christchurch waste water system are as follows:

- Continue to collate data and analyse pipe material performance;
- Characterise modes of failure waste for the waste water system using CCTV and profilometer data
- Identify key factors/contributors to the damage of the waste water network
- Establish *LRI*-based correlations for representative materials of waste water pipelines in the same fashion as explained for the potable water network.
- Further update, scrutiny and analysis of the damage data on the potable water network and refinement of preliminary findings.

5.0 Road Network

5.1 Introduction

Road networks are critical infrastructure lifelines, and the CES has had a significant impact on Christchurch's transport system. Presented below are initial findings from an analysis of lateral spreading damage to bridges (Cubrinovski et al., 2013b), along with an overview of liquefaction ejecta clean-up from Christchurch city's roads through the CES (Villemure, 2013; Villemure et al., in prep).

5.2 Road network characteristics

As of February 2013, Christchurch road surface materials were dominantly comprised of single coat seal (51%), followed by two coat seal (27%) and asphaltic concrete (12%) (Figure 45). The remainder of the network has road surfaces comprised of a variety of materials (Table 6).

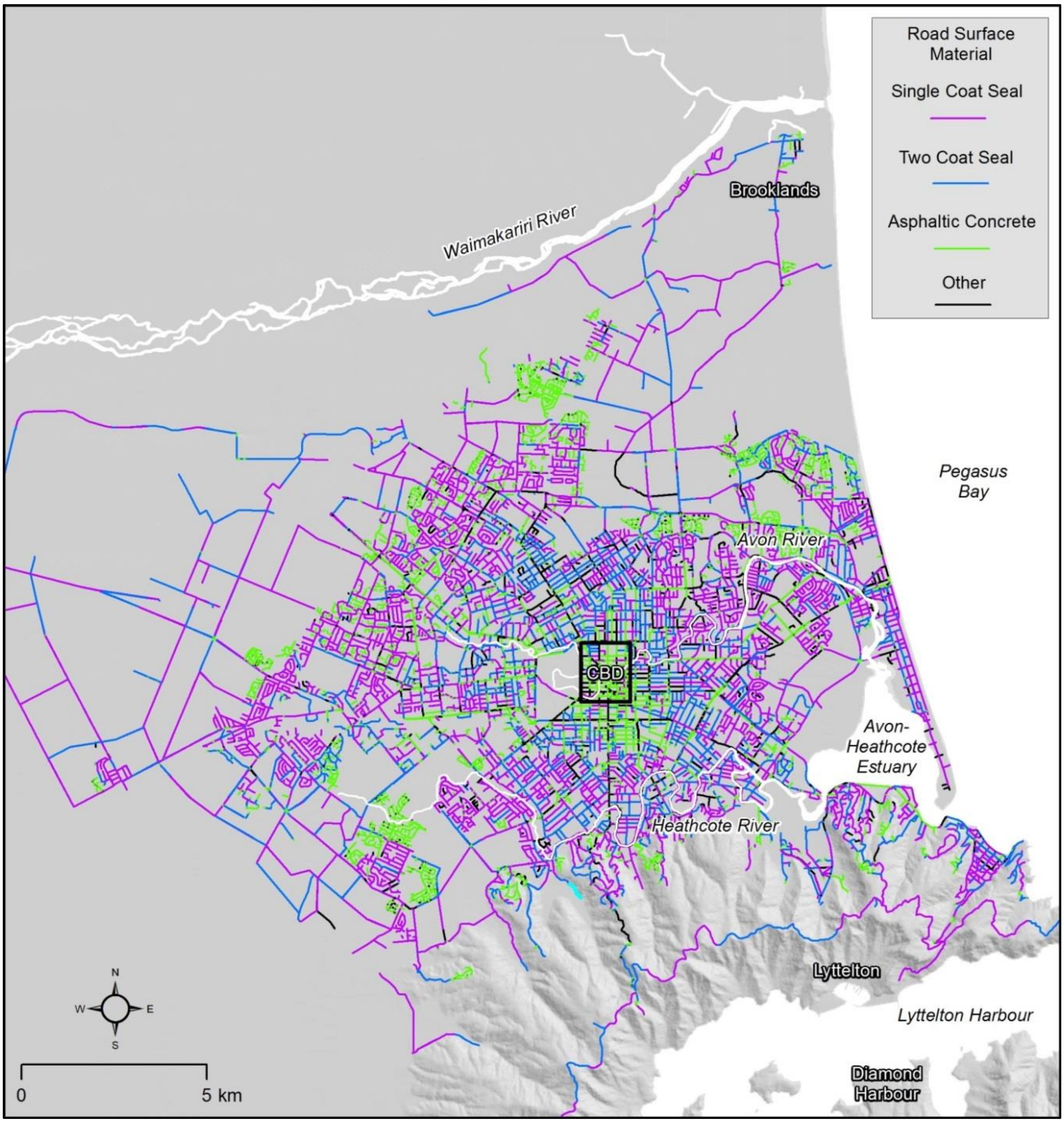


Figure 45. Christchurch City road surface materials.

Table 6. Road surface materials in the Christchurch City urban area.

Road Surface	Length (km)	Percentage of Network
Single Coat Seal	1707.662	51
Two Coat Seal	909.043	27
Asphaltic concrete	392.569	12
Open graded emulsion mix	121.177	4
Open Graded Porous Asphalt	93.231	3
Slurry Seal	66.002	2
Interlocking concrete blocks	14.901	<1
Void fill seal	7.975	<1
Bicouche/Sandwich	4.638	<1
Concrete	2.227	<1
Racked in Seal	0.847	<1
Other material type	0.422	<1
Metal running course	0.399	<1
Stone Mastic Asphalt	0.187	<1
Texturising Seal	0.184	<1
Prime and seal	0.150	<1
Total	**3321.614**	**100**

5.3 Impacts of the 22 February 2011 Christchurch Earthquake

Immediately after the 22 February 2011 Christchurch Earthquake, twelve crews of CCC engineers conducted detailed drive-through reconnaissance, covering nearly all roads in the Christchurch urban area, to assess road damage and estimate the cost of repairs. Over a period of ten weeks, the inspection teams documented data on the damage and made detailed observations on the road surface, kerb/channel and footpath conditions (McNeill & English, 2011). These damage data were compiled and synthesized into the road damage map shown in Figure 46, which indicates three levels of road damage: major, moderate and minor.

Using these road damage data in conjunction with the liquefaction map presented in Figure 7 (Top) (also shown in the background of Figure 46), a geospatial analysis was performed using GIS to correlate the severity of road damage with the liquefaction severity. The results of the analysis indicate a very strong correlation between the level of road damage and severity of liquefaction manifestation (Table 7). Practically all major damage to roads (i.e. 97%) occurred in areas of moderate or severe liquefaction; 80% of the moderate road damage occurred in areas of moderate to severe liquefaction, while the remaining 20% of the moderate road damage was observed in areas of minor or no liquefaction manifestation. The minor road damage was spread over the entire area of Christchurch, reflecting the high levels of accelerations and ground distress caused by the local earthquakes throughout the city.

Overall, in the 2010-2011 earthquakes road bridges performed relatively well compared to other engineering structures (Palermo et al., 2011; Wotherspoon et al., 2011). They suffered low to moderate damage and all but one bridge were in service almost immediately after each significant event. A general overview of the damage to road bridges (longer than 10 m) in the urban area of

Christchurch, as judged per visual inspections of Opus engineers for CCC (CCC, 2011b), is depicted in Figure 47.

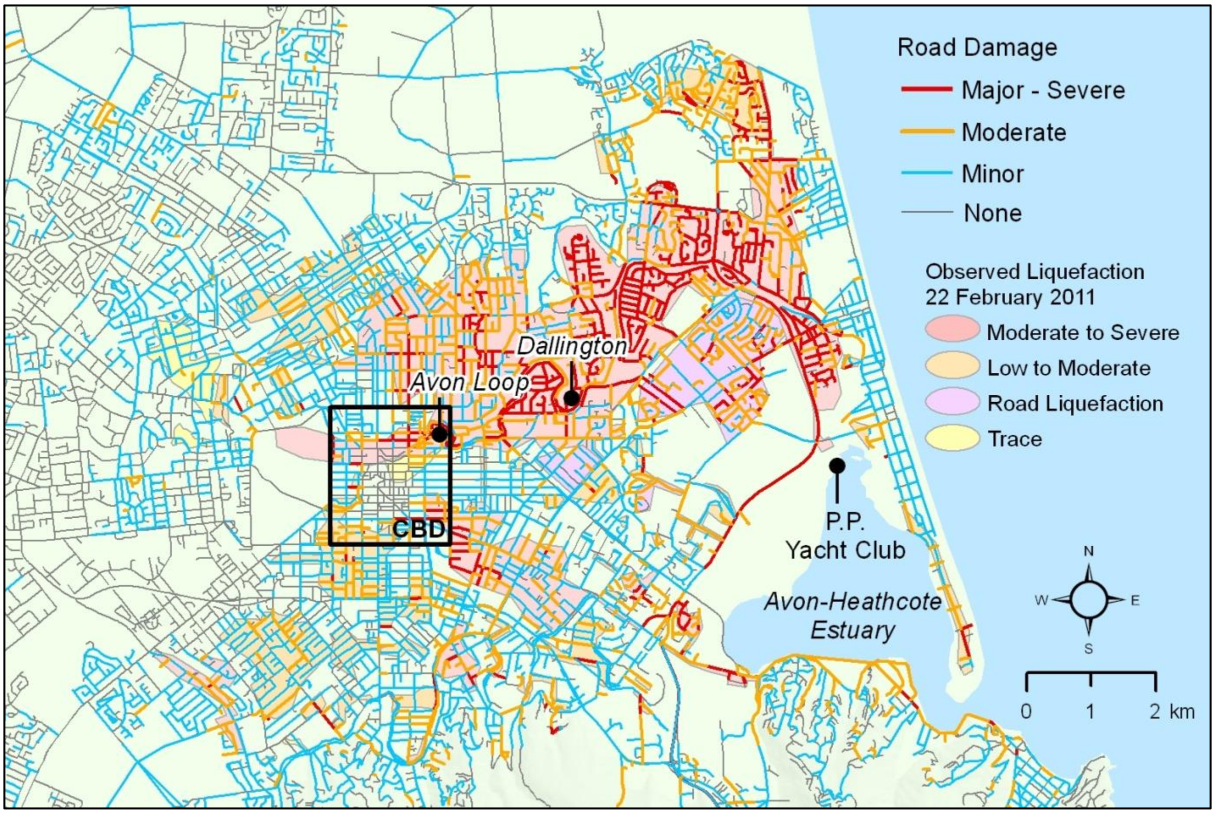


Figure 46. Christchurch City road damage post-22 February 2011, based on CCC classifications. UC liquefaction observations also shown. From Cubrinovski et al. (2013b).

Table 7. Lengths of road damage classes as determined by the Christchurch City Council within areas of observed liquefaction (mapped by UC) on 22 February 2011. From Cubrinovski et al. (2013b).

		Road Damage (km)				
		Severe	Major	Moderate	Minor	Minimal
Observed Liquefaction	Moderate-Severe	37.922	39.409	79.022	40.044	9.032
	Low-Moderate	1.700	5.851	31.288	41.158	18.573
	Road Liquefaction	0.941	3.700	16.296	8.447	2.036
	Trace	-	-	2.160	8.523	4.802
	None	0.941	1.981	30.076	93.412	77.093

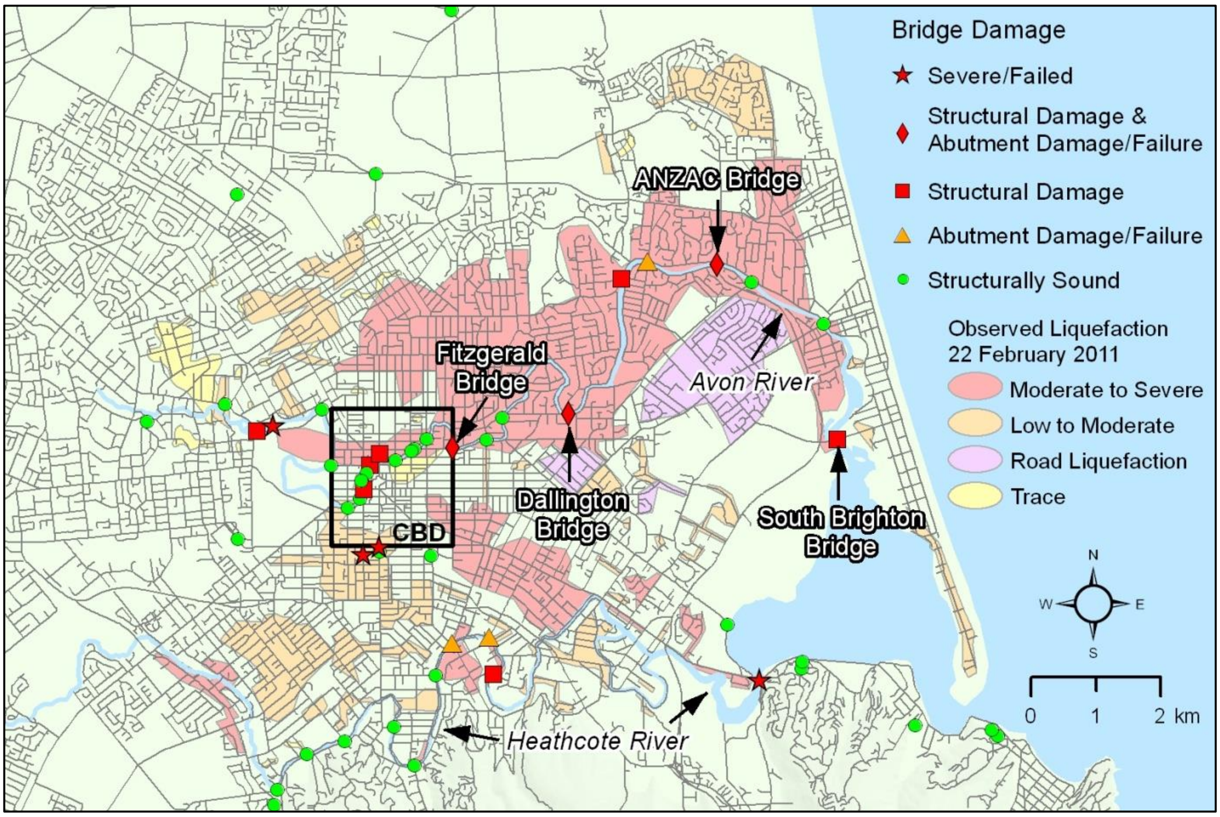


Figure 47. Bridge damage classifications post-22 February 2011. Data from SCIRT. UC liquefaction observations also shown. From Cubrinovski et al. (2013b).

The road damage data collection conducted by CCC included road pavement condition that described the areal extent of identified road surface collapses (>10 m^2, 5-10 m^2, <5 m^2) and locations of road surface unevenness (Figure 48). In addition, observations after rainfall events identified locations of water ponding on road surfaces that had not occurred prior to the CES (Figure 49).

The repeated manifestation of liquefaction ejecta through the CES resulted in repeated burial of road surfaces. The most comprehensive investigation of liquefaction ejecta clean-up has been conducted by Villemure (2013) and Villemure et al. (in prep). This work included interviews with the primary road clean-up contractors Fulton Hogan (FH) and CCL. Detailed reviews of FH records revealed minimal information on tonnages of liquefaction ejecta after major events, although there was abundant information of resources used in, and costing of, the clean-up. The major findings from this work are:

- Emergency planning and the use of the coordinated incident management system (CIMS) system during the emergency were important to facilitate rapid clean-up tasking, management of resources and ultimately recovery from widespread and voluminous liquefaction ejecta deposition in eastern Christchurch;
- Over 500,000 tonnes of ejecta was been stockpiled at Burwood landfill for all major liquefaction-inducing earthquake events;
- The average cost per kilometre for the event clean-up was $NZ 5,500/km (4 September 2010), $NZ 11,650/km (22 February 2011) and $NZ 11,185/km (13 June 2011);

5.4 On-going and future research

The next steps in analysis of the Christchurch road network are as follows:

- Review of CCC road damage data to identity information most useful for mechanistic understanding of road damage.
- Detailed characterisation of road surface material properties, including construction specifications. Observations by CCC road engineers suggest different construction techniques were variously susceptible to penetration by liquefaction ejecta, and these modes of failure need to be classified.
- Characterise road damage by liquefaction severity through the *LRI* concept.

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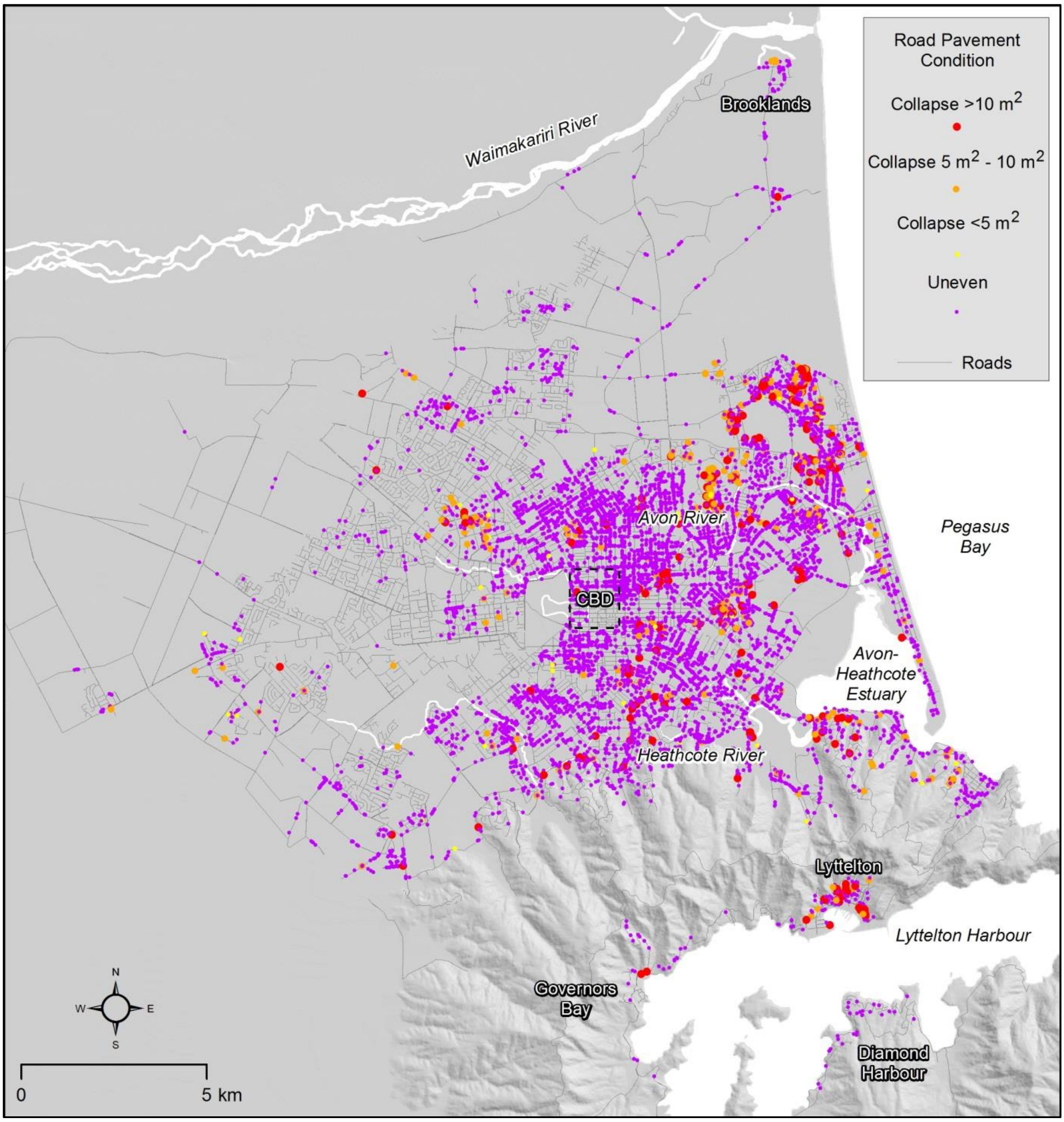

Figure 48. Road pavement condition across Christchurch City after the 22 February 2011 Christchurch Earthquake.

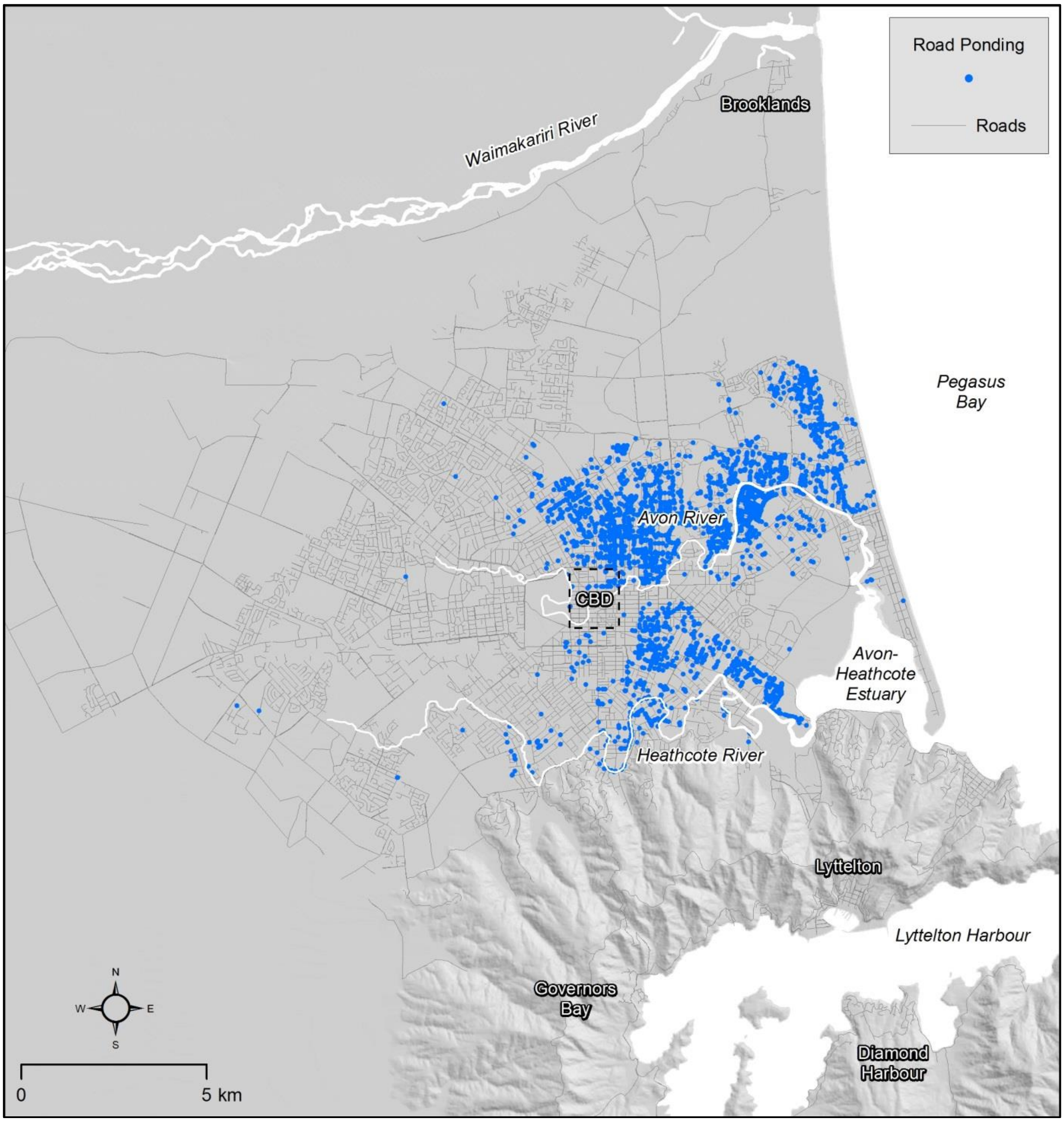

Figure 49. Road ponding across Christchurch City after the 22 February 2011 Christchurch Earthquake.

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Appendix A - Summary repair data for the potable supply network across Christchurch City and Banks Peninsula District according to pipe material and diameter.

Pipe Material	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
MPVC	4463	149.198	34	2.476	36	0.2
PVC	12548	409.499	218	23.287	275	0.7
MDPE80	21055	463.258	331	19.173	372	0.8
DI	2856	61.622	43	2.738	52	0.8
HDPE	37055	931.712	1407	82.188	1744	1.9
AC	20993	770.809	1139	84.252	1747	2.3
S	1275	35.267	70	6.132	94	2.7
CI	7199	192.628	419	31.104	609	3.2
CLS	1614	52.058	103	10.243	168	3.2
GI	14769	186.543	1210	42.691	1651	8.9
Total	**123814**	**3252.149**	**4974**	**347.897**	**6738**	**2.1**

Appendix B - Summary repair data for the potable supply network across Christchurch City and Banks Peninsula District according to pipe material and diameter.

M-Polyvinyl Chloride						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
50	4	0.055	-	-	-	-
63	33	0.975	-	-	-	-
75	2	0.031	-	-	-	-
100	1915	48.903	16	0.986	17	0.3
150	1439	54.192	12	1.024	12	0.2
200	917	37.013	6	0.466	7	0.2
300	153	8.029	-	-	-	-
Total	**4463**	**149.198**	**34**	**2.476**	**36**	**0.2**

Polyvinyl Chloride						
Diameter	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	30	1.904	1	0.089	1	0.5
25	314	10.830	10	0.458	10	0.9
32	160	3.925	2	0.103	2	0.5
38	20	0.564	1	0.088	1	1.8
40	504	16.847	15	1.101	17	1.0
50	1368	36.640	32	2.346	24	0.7
63	18	0.205	-	-	-	-
65	16	4.010	-	-	-	-
75	11	0.998	2	0.528	3	3.0
80	156	3.059	1	0.064	1	0.3
100	4612	134.834	79	8.347	118	0.9
150	2914	96.157	47	47	55	0.6
175	43	5.242	2	1.094	2	0.4
200	1616	59.346	18	3.722	21	0.4
225	6	0.270	-	-	-	-
250	4	0.020	-	-	-	-
300	669	31.591	7	1.492	9	0.3
375	42	1.483	1	0.470	1	0.7
400	2	0.006				
450	1	0.002				
600	2	0.002				
Total	**12535**	**409.054**	**218**	**66.901**	**265**	**0.6**

Medium-Density Polyethylene 80						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
25	114	0.983	1	0.066	1	1.0
32	848	11.429	7	0.082	10	0.9
50	6388	230.481	178	9.569	202	0.9
63	13632	215.196	145	9.456	159	0.7
65	3	0.093	-	-	-	-
75	4	0.005	-	-	-	-
100	20	0.362	-	-	-	-
125	6	0.188	-	-	-	-
150	14	3.941	-	-	-	-
200	1	0.0004	-	-	-	-
250	2	0.030	-	-	-	-
Total	**21055**	**463.258**	**331**	**19.173**	**372**	**0.8**

Ductile Iron						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
50	2	0.0004	-	-	-	-
100	438	5.729	9	0.297	9	1.6
125	3	0.008	-	-	-	-
150	684	12.198	7	0.306	7	0.6
200	1090	22.481	15	0.764	18	0.8
225	6	0.027	-	-	-	-
250	26	0.125	-	-	-	-
300	584	20.388	12	1.371	18	0.9
375	12	0.555	-	-	-	-
400	1	0.006	-	-	-	-
450	10	0.105	-	-	-	-
Total	**2856**	**61.621**	**43**	**2.738**	**52**	**0.8**

High-Density Polyethylene						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
13	63	1.532	-	-	-	-
15	38	0.959	-	-	-	-
20	524	10.754	18	1.118	25	2.3
25	7444	189.146	370	15.473	460	2.4
32	590	10.504	11	1.632	14	1.3
38	95	3.824	9	0.763	10	2.6
40	9977	410.400	569	39.626	715	1.7
50	18317	304.509	430	23.575	520	1.7
63	7	0.086	-	-	-	-
Total	**37055**	**931.712**	**1407**	**82.188**	**1744**	**1.9**

Asbestos Cement						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs	Repairs/ km
50	343	15.587	15	2.381	23	1.5
75	79	2.348	2	0.207	2	0.9
80	16	0.415	1	0.086	1	2.4
100	12182	413.136	836	57.092	1287	3.1
150	6621	250.103	315	23.457	423	1.7
200	3386	126.402	169	13.073	223	1.8
225	71	2.871	15	1.404	19	6.6
250	181	8.495	7	0.997	8	0.9
300	1168	51.672	40	7.547	60	1.2
375	98	6.080	3	0.535	5	0.8
Total	**24145**	**877.109**	**1403**	**106.780**	**2051**	**2.3**

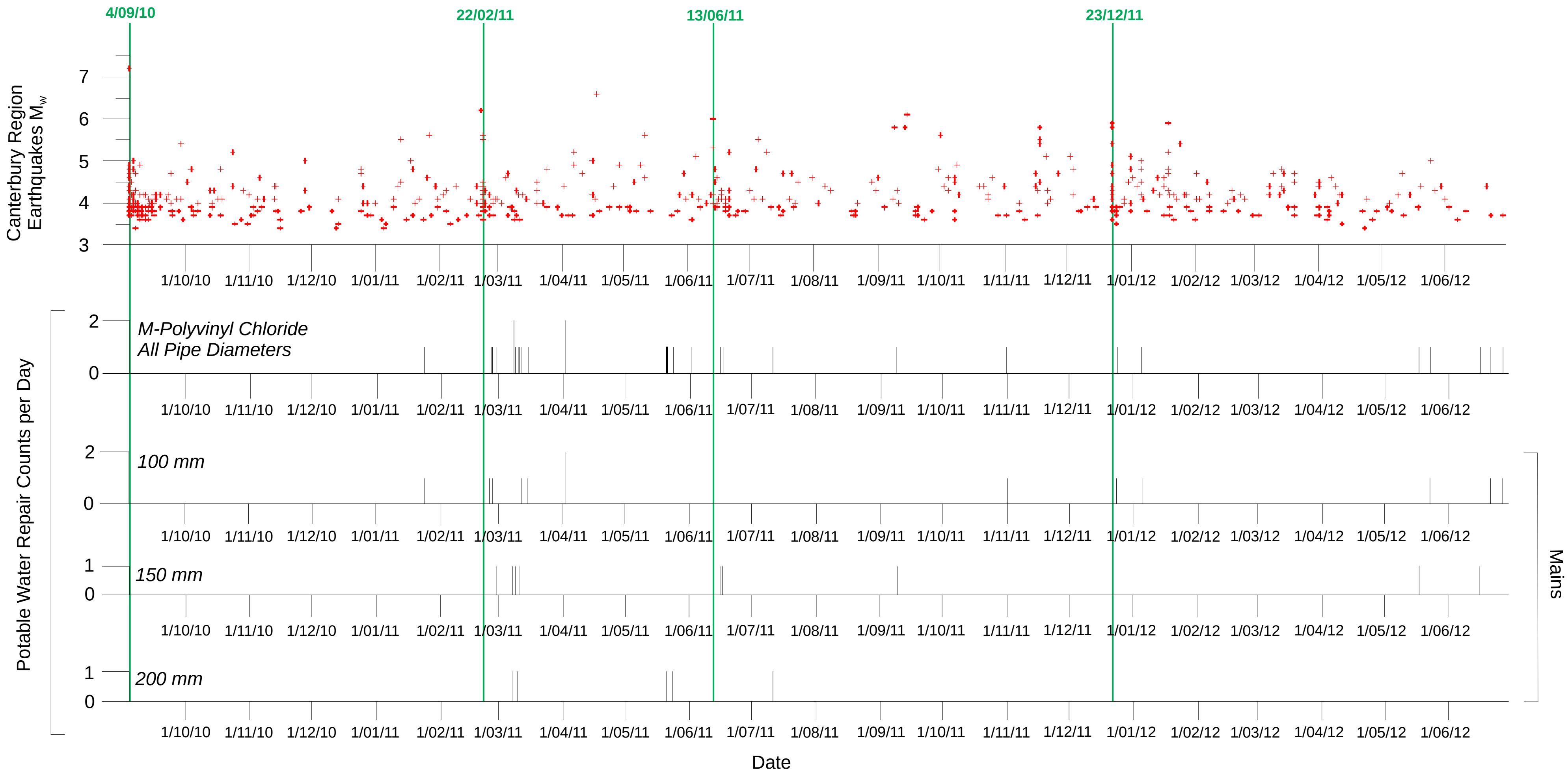
Steel						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
25	1	0.003	-	-	-	-
40	2	0.013	-	-	-	-
50	1	0.212	-	-	-	-
75	6	0.410	1	0.387	1	2.4
80	17	0.586	1	0.010	1	1.7
100	445	10.922	40	3.074	56	5.1
150	299	6.203	20	1.801	28	4.5
175	7	0.086	-	-	-	-
200	211	3.578	2	0.310	2	0.6
250	19	0.328	-	-	-	-
300	158	1.964	3	0.174	3	1.5
375	31	2.702	2	0.370	2	0.7
425	2	0.224	-	-	-	-
450	15	1.848	-	-	-	-
550	23	4.661	-	-	-	-
600	38	1.527	1	0.005	1	0.7
Total	**1275**	**35.267**	**70**	**6.132**	**94**	**2.7**

Cast Iron						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs	Repairs/ km
38	4	0.281	-	-	-	-
75	164	2.636	8	0.395	10	3.8
80	98	3.469	10	1.032	10	2.9
100	3903	109.926	269	18.966	394	3.6
125	14	0.561	1	0.086	1	1.8
150	1679	39.374	74	4.282	117	3.0
200	1238	34.115	50	5.755	67	2.0
250	10	0.085	-	-	-	-
300	89	2.180	7	0.588	10	4.6
Total	**7199**	**192.628**	**419**	**31.104**	**609**	**3.2**

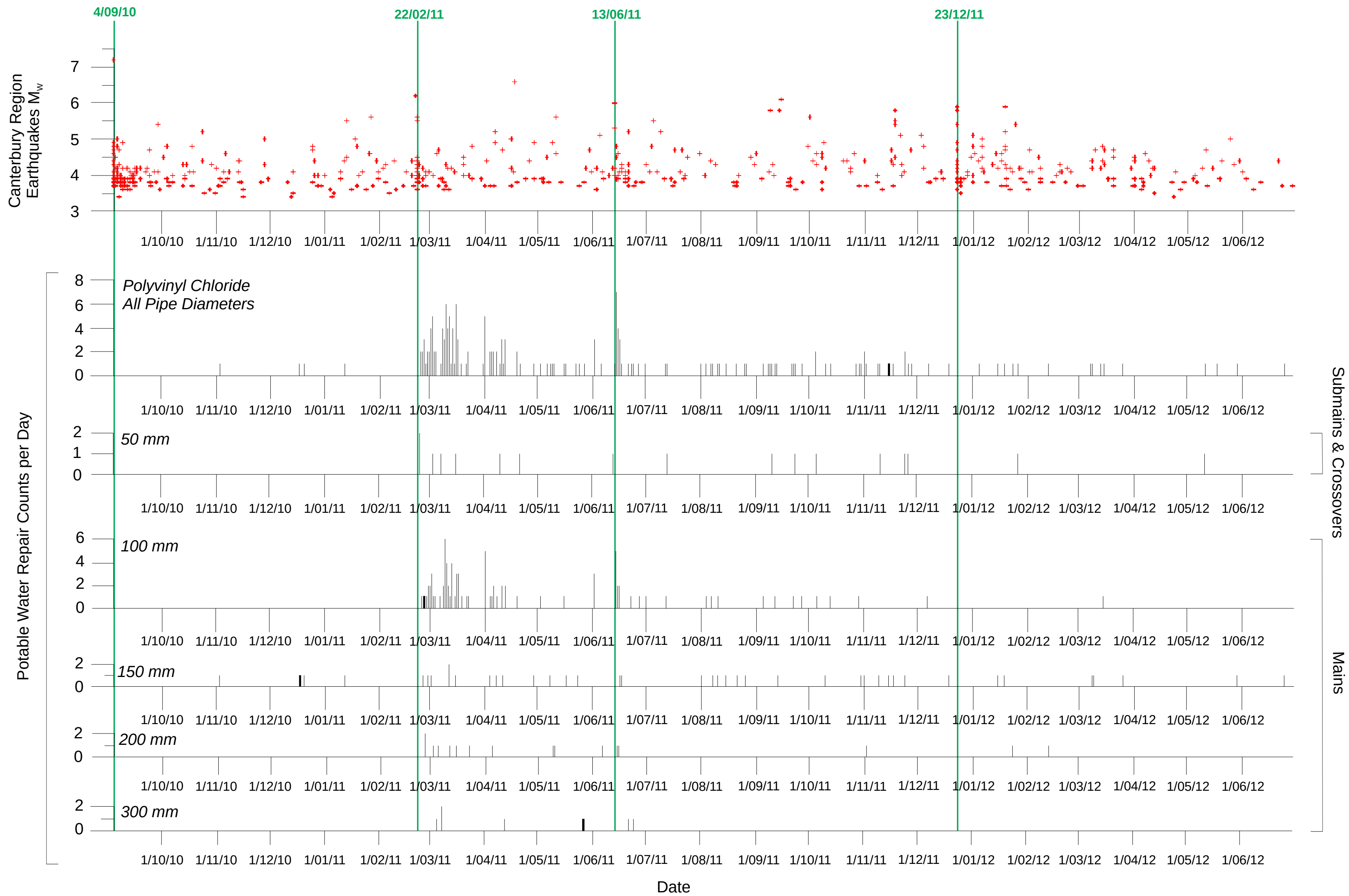
Concrete-Lined Steel						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs	Repairs/ km
75	2	0.002	-	-	-	-
100	300	9.519	56	3.930	111	11.7
150	91	2.471	7	0.343	14	5.7
200	359	4.625	6	0.301	6	1.3
225	22	0.069	-	-	-	-
250	69	2.798	7	1.740	6	2.1
300	570	17.213	14	1.079	16	0.9
375	94	5.482	8	1.556	10	1.8
425	1	0.016	-	-	-	-
450	69	6.184	2	0.678	2	0.3
600	37	3.679	3	0.615	3	0.8
Total	**1614**	**52.058**	**103**	**10.243**	**168**	**3.2**

Galvanised Iron						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
13	12	0.281	2	0.119	2	7.1
15	32	0.701	3	0.016	4	5.7
20	5074	90.474	767	27.546	1075	11.9
25	5881	46.996	242	6.854	305	6.5
32	146	2.995	7	0.619	16	5.3
38	51	1.360	2	0.049	2	1.5
40	537	12.249	53	3.235	85	6.9
50	2849	28.321	128	3.920	155	5.5
65	8	0.058	-	-	-	-
75	63	1.174	6	0.332	7	6.0
80	8	0.039	-	-	-	-
100	23	0.802	-	-	-	-
150	63	1.030	-	-	-	-
200	21	0.061	-	-	-	-
300	1	0.002	-	-	-	-
Total	**14769**	**186.543**	**1210**	**42.691**	**1651**	**8.9**

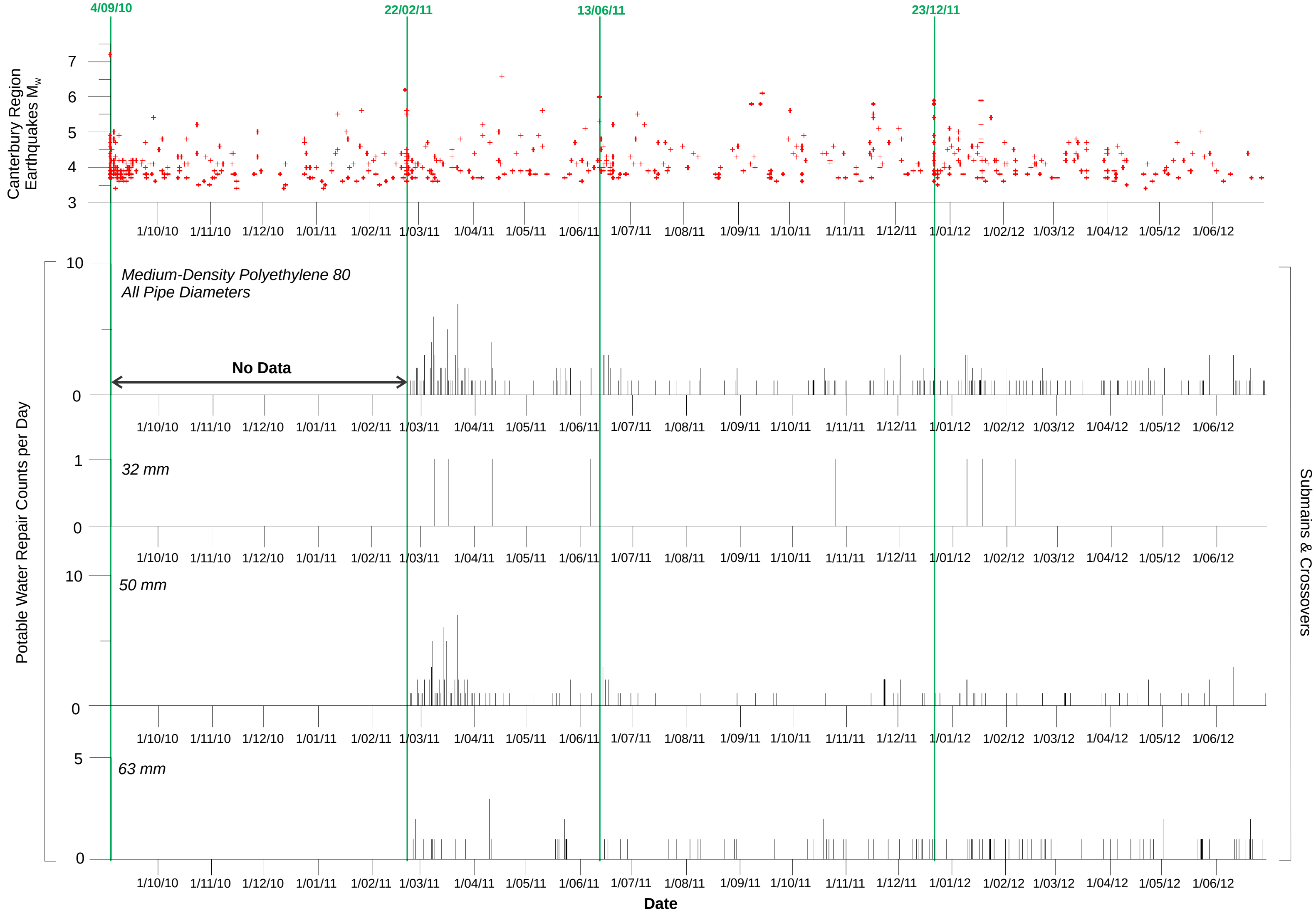
Appendix C – Frequency of pipe repairs through the Canterbury Earthquake Sequence.



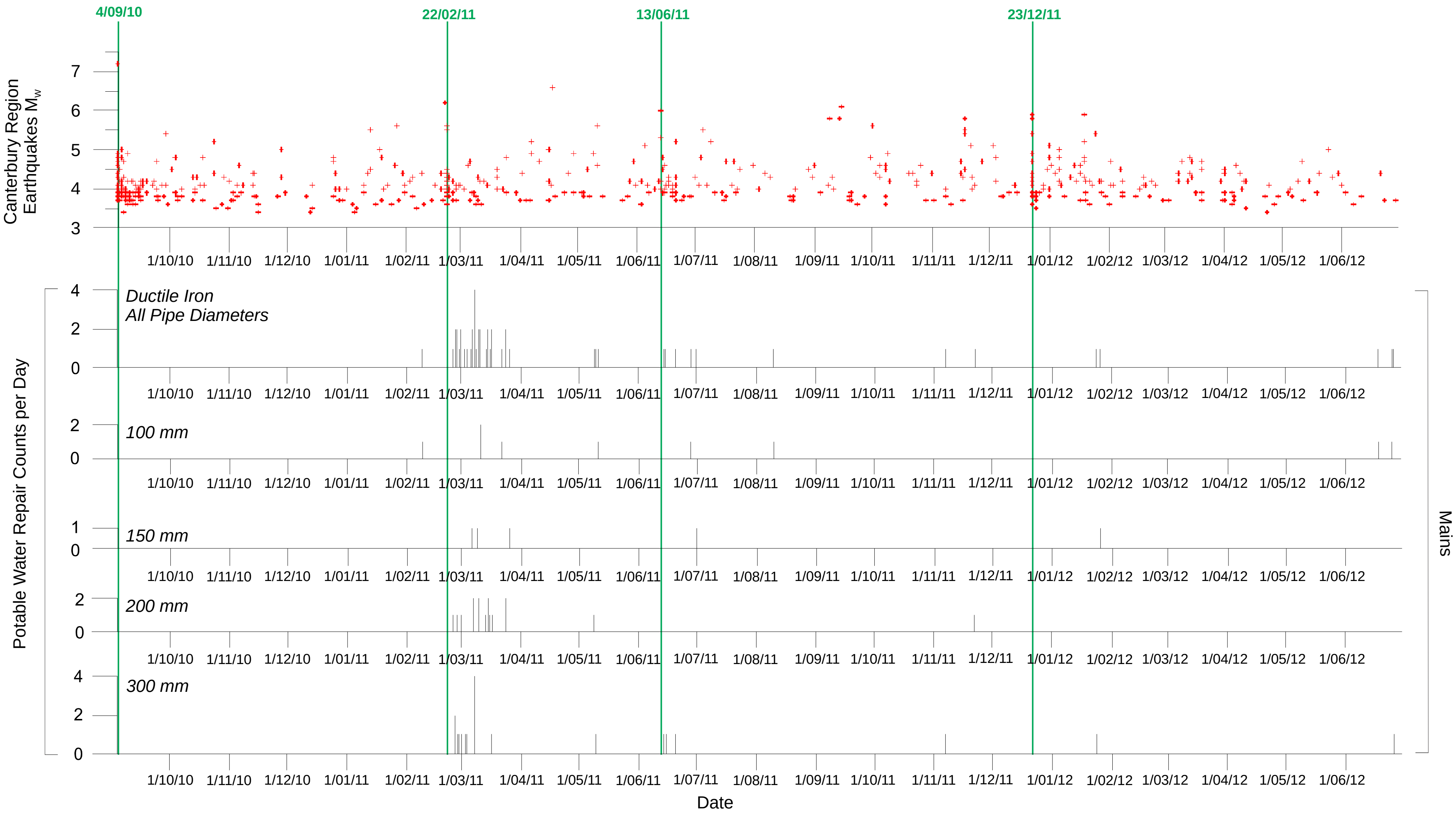
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for MPVC pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



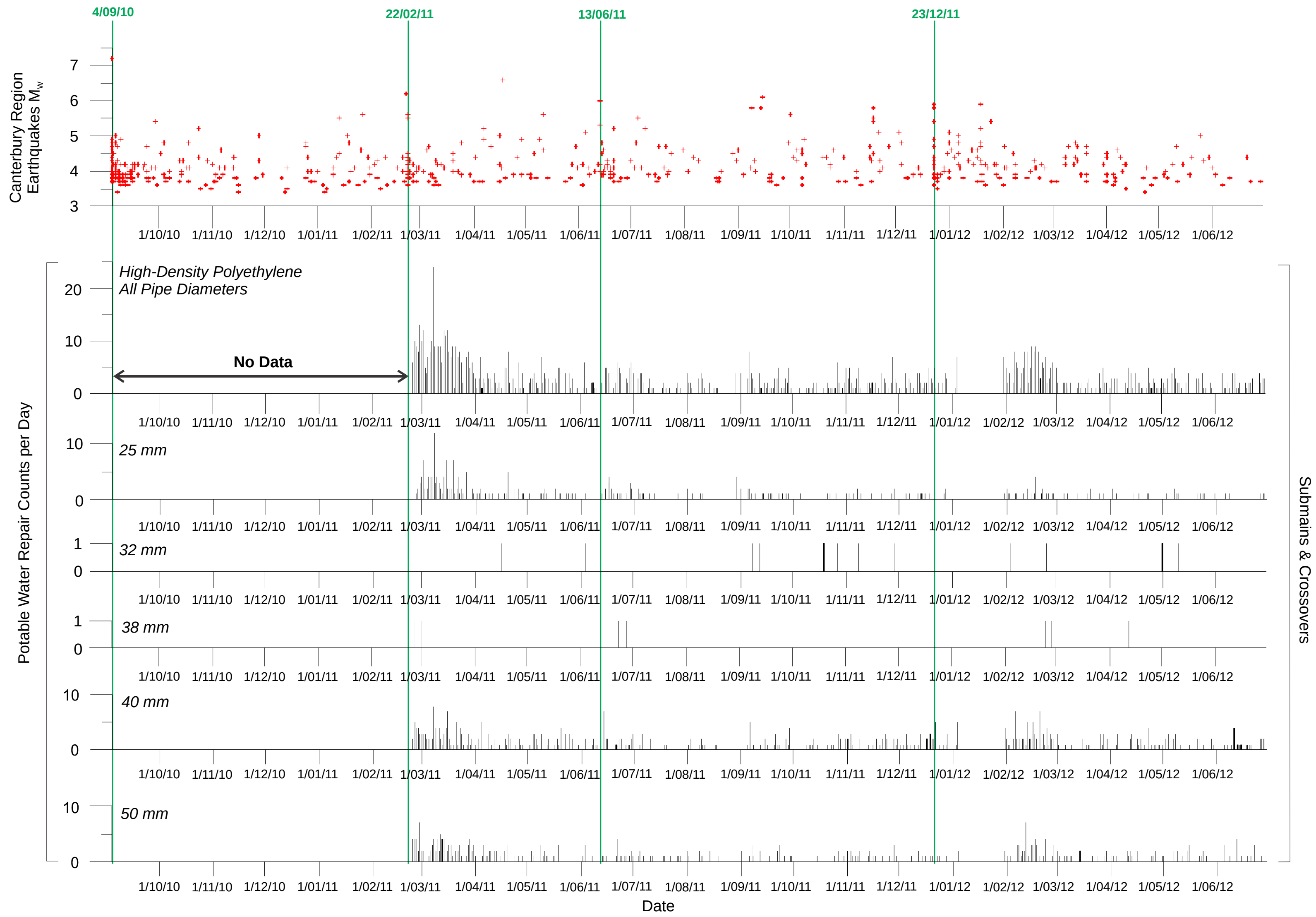
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for PVC pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



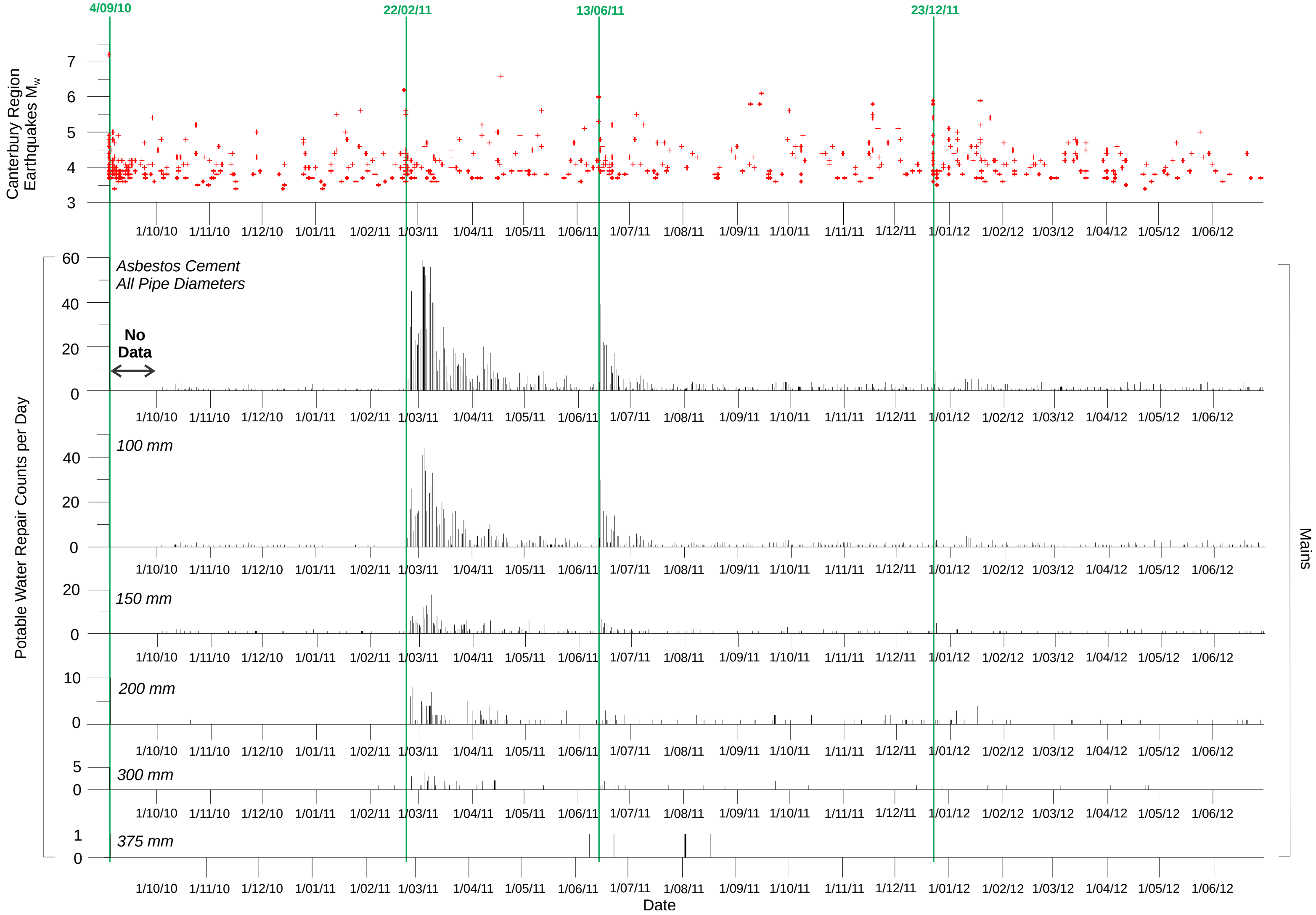
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for MDPE80 pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



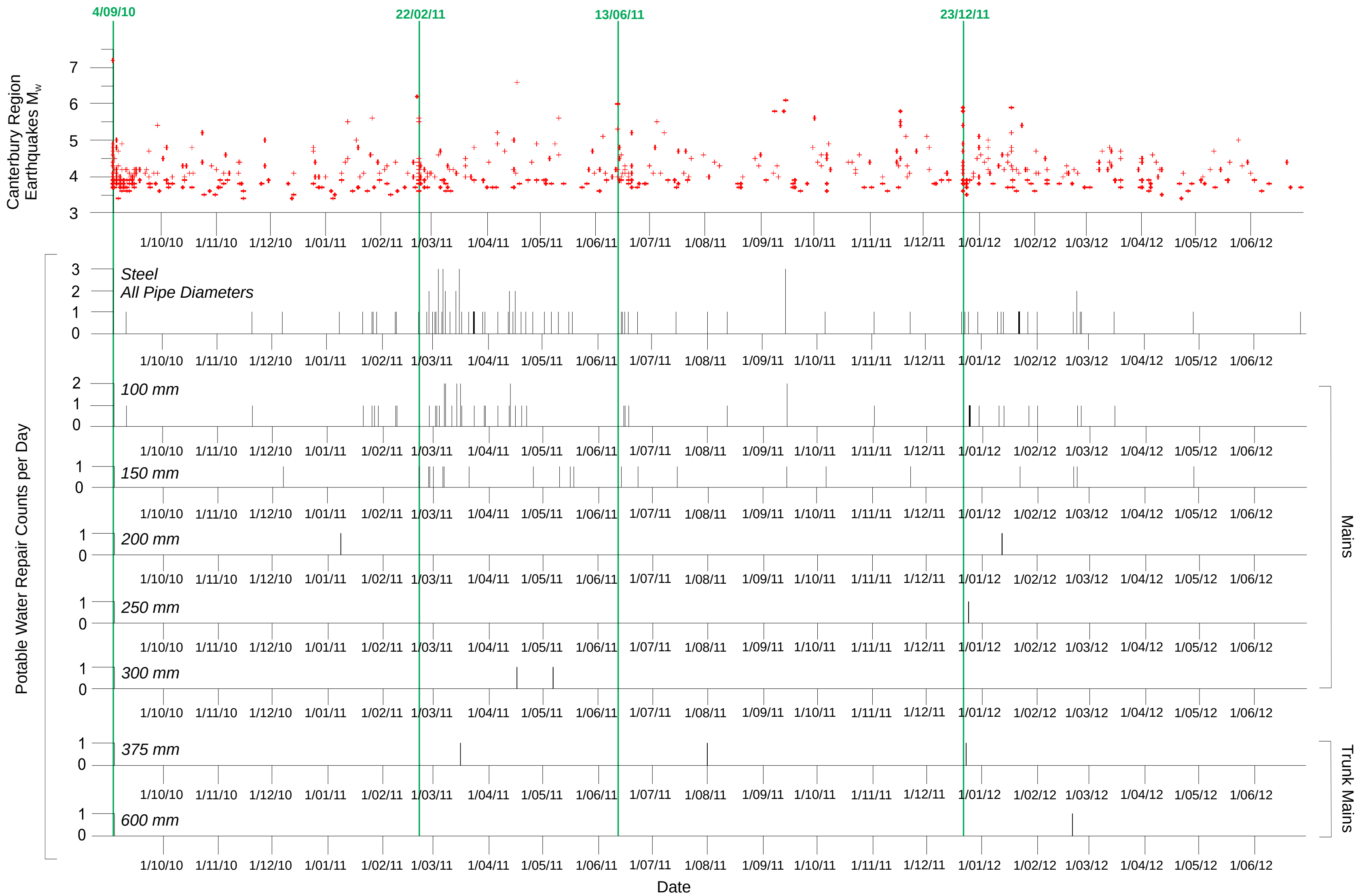
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for DI pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



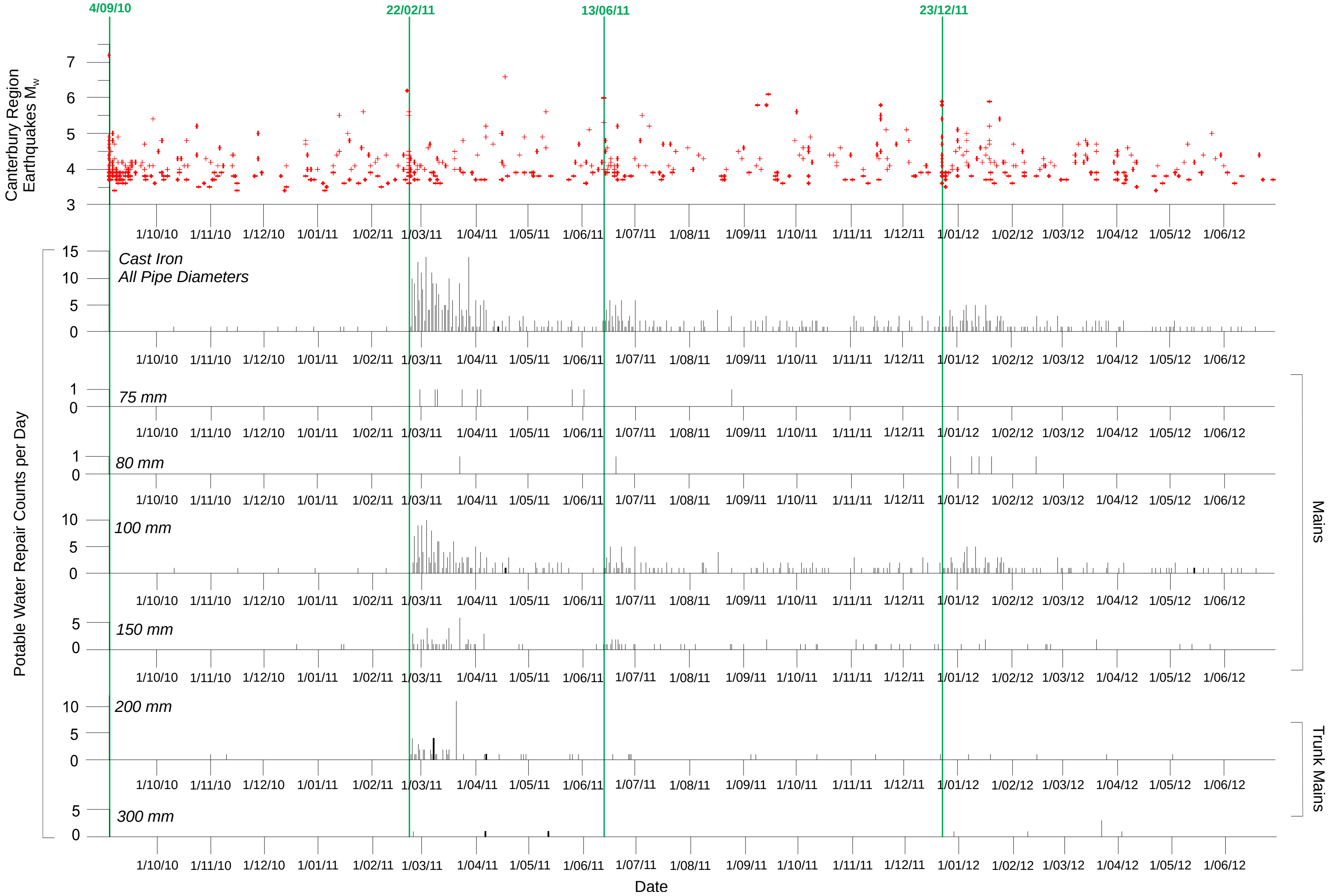
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for HDPE pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



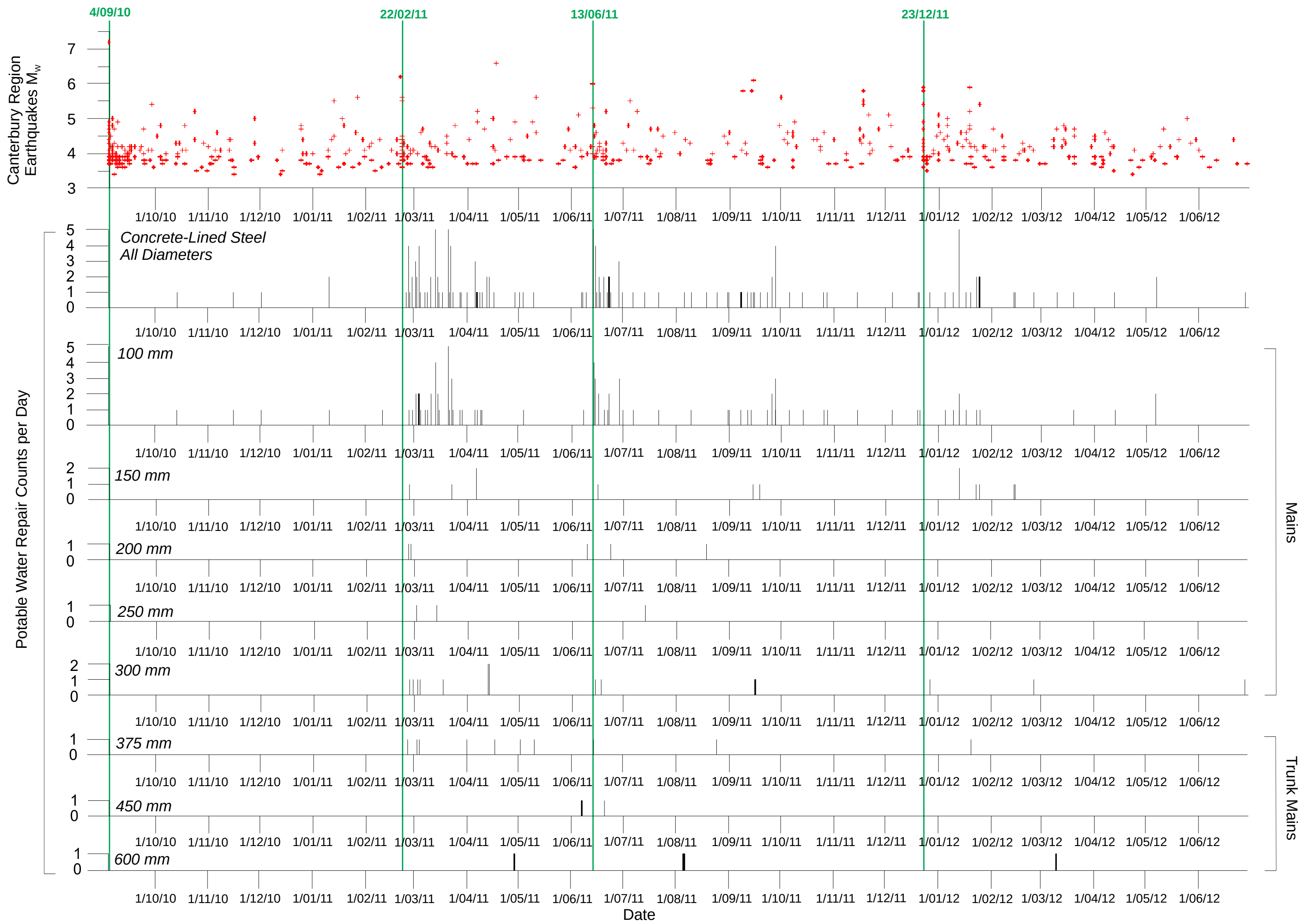
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for AC pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



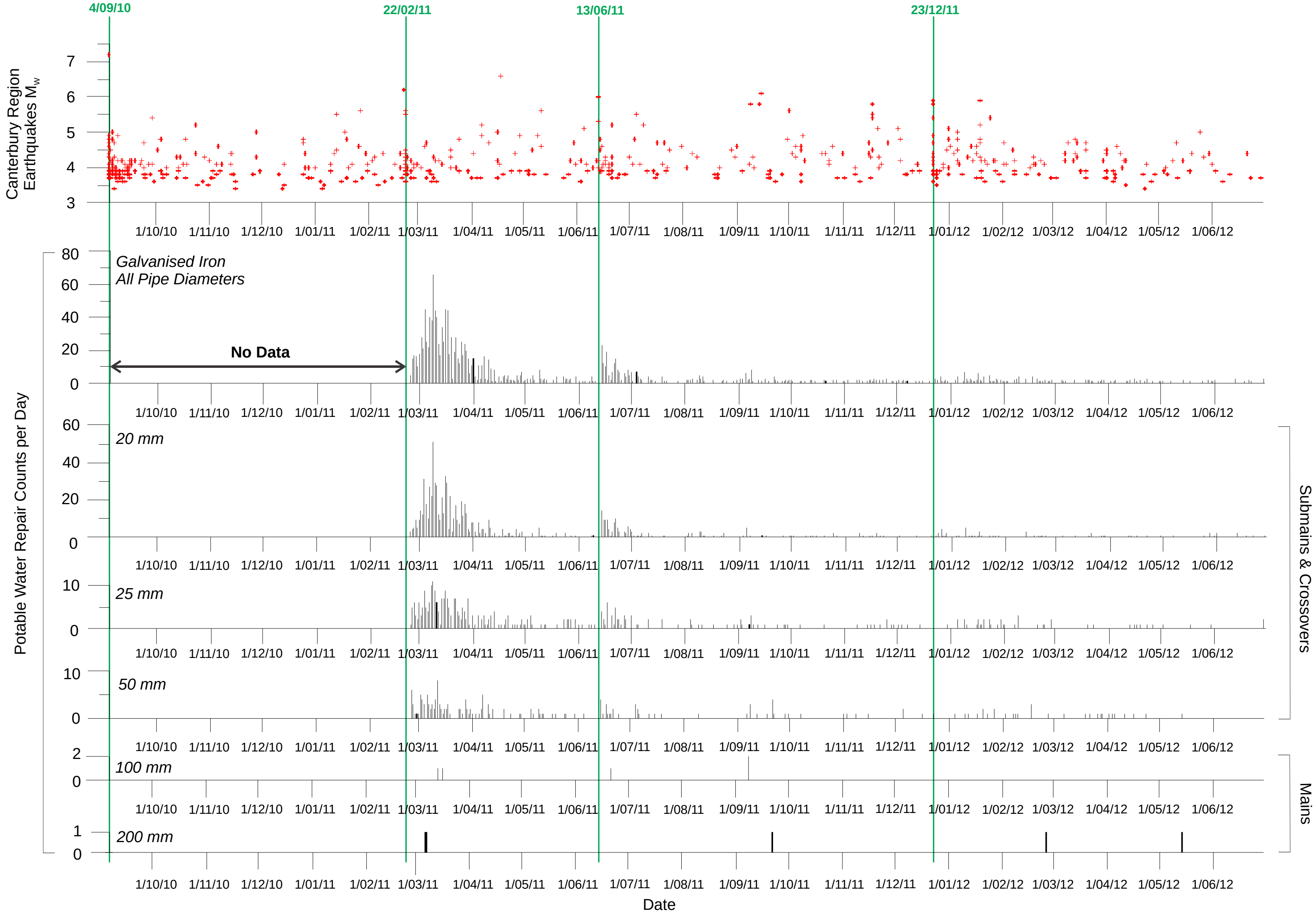
Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for Steel pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for CI pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for CLS pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.



Time line of Canterbury Region earthquakes (M_w) and repair job creation dates for GI pipes through the Canterbury Earthquake Sequence, 4 September 2010 to 30 June 2012.

Appendix D - Summary repair data for the potable supply network across Christchurch City according to pipe material and Liquefaction Resistance Index Zone.

M-Polyvinyl Chloride						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	32	1.223	5	0.307	6	4.9
1	257	8.217	8	0.426	9	1.1
2	589	17.911	4	0.337	4	0.2
3	861	26.345	2	0.065	2	0.0
4	1739	53.696	-	-	-	-
No Obs	1493	50.481	5	0.426	5	0.1
Total	**4971**	**157.872**	**24**	**1.561**	**26**	**0.2**

Polyvinyl Chloride						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	241	9.541	33	2.474	66	6.9
1	1066	33.896	36	3.244	43	1.3
2	1516	44.352	28	2.305	29	0.7
3	7887	237.760	18	1.614	21	0.1
4	2007	56.438	12	3.302	12	0.2
No Obs	2849	90.764	28	3.750	27	0.3
Total	**15566**	**472.750**	**155**	**16.688**	**198**	**0.4**

Medium-Density Polyethylene 80						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	1009	21.832	45	2.293	61	2.8
1	2299	47.580	44	1.842	50	1.1
2	2807	63.436	54	3.501	58	0.9
3	4572	94.746	81	4.071	88	0.9
4	2187	49.087	11	0.713	11	0.2
No Obs	5628	124.755	66	5.260	71	0.6
Total	**18502**	**401.437**	**301**	**17.681**	**339**	**0.8**

Ductile Iron						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	23	0.721	6	0.398	8	11.1
1	412	0.041	17	1.283	22	2.4
2	327	9.406	5	0.312	6	0.6
3	911	17.355	6	0.172	6	0.3
4	118	2.952	-	-	-	-
No Obs	508	12.619	2	0.160	3	0.2
Total	**2299**	**52.095**	**36**	**2.325**	**45**	**0.9**

High-Density Polyethylene						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	1033	25.833	103	5.215	128	5.0
1	5000	119.291	273	14.631	346	2.9
2	6252	160.997	259	14.592	347	2.2
3	9685	243.806	363	20.127	466	1.9
4	4330	107.199	53	3.840	61	0.6
No Obs	7038	185.502	215	15.060	234	1.3
Total	**33338**	**842.628**	**1266**	**73.465**	**1582**	**1.9**

Asbestos Cement						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	516	17.949	142	8.546	250	13.9
1	2110	69.963	328	21.262	525	7.5
2	3156	111.639	142	8.546	250	2.2
3	5189	177.343	253	18.234	367	2.1
4	4470	177.802	68	6.047	79	0.4
No Obs	5552	216.113	206	21.618	276	1.3
Total	**20993**	**770.809**	**1139**	**84.252**	**1747**	**2.3**

Concrete-Lined Steel						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	30	1.187	11	0.710	22	18.5
1	354	12.781	52	3.587	104	8.1
2	207	5.996	7	0.905	7	1.2
3	536	13.026	9	0.684	10	0.8
4	30	1.945	-	-	-	-
No Obs	321	13.808	16	3.122	18	1.3
Total	**1478**	**48.744**	**95**	**9.008**	**161**	**3.3**

Steel						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	7	0.013	-	-	-	-
1	138	38.368	29	2.301	43	1.1
2	207	5.637	12	0.960	13	2.3
3	274	5.478	13	1.055	18	3.3
4	60	3.221	1	0.091	1	0.3
No Obs	180	6.392	10	0.806	13	2.0
Total	**866**	**59.110**	**65**	**5.213**	**88**	**1.5**

Galvanised Iron						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	535	7.540	115	4.105	188	24.9
1	2318	27.000	287	9.641	393	14.6
2	3064	35.288	296	9.975	412	11.7
3	3836	45.019	227	8.655	287	6.4
4	584	10.061	6	0.263	6	0.6
No Obs	1964	27.170	102	4.076	147	5.4
Total	**12301**	**152.077**	**1033**	**36.714**	**1433**	**9.4**

Appendix E - Summary repair data for the potable supply network across Christchurch City according to pipe material, diameter and Liquefaction Resistance Index zone

Medium-Density Polyethylene-80

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
32	39	0.739	-	-	-	-
50	415	17.212	37	1.876	49	2.8
63	554	3.805	8	0.418	12	3.2
150	1	0.075	-	-	-	-
Total	**1009**	**21.832**	**45**	**2.293**	**61**	**2.8**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	2	0.006	-	-	-	-
25	5	0.034	-	-	-	-
32	77	0.926	2	0.036	3	3.2
50	1042	39.298	31	1.693	36	0.9
63	1166	7.019	11	0.113	11	1.6
100	3	0.156	-	-	-	-
150	4	0.142	-	-	-	-
Total	**2299**	**47.580**	**44**	**1.842**	**50**	**1.1**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
15	1	0.009	-	-	-	-
20	1	0.027	-	-	-	-
25	20	0.167	-	-	-	-
32	93	1.165	-	-	-	-
50	900	32.133	20	1.169	20	0.622
63	1789	29.934	34	2.332	38	1.269
100	1	0.000	-	-	-	-
150	2	0.001	-	-	-	-
Total	**2807**	**63.436**	**54**	**3.501**	**58**	**0.9**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
15	4	0.184	-	-	-	-
20	5	0.171	-	-	-	-
25	20	0.145	-	-	-	-
32	177	2.409	3	0.031	5	2.1
50	1586	58.306	47	2.223	50	0.9
63	2764	33.302	31	1.817	33	1.0
100	9	0.009	-	-	-	-
125	6	0.188	-	-	-	-
150	1	0.033	-	-	-	-
Total	**4572**	**94.746**	**81**	**4.071**	**88**	**0.9**

Summary repair data for Medium-Density Polyethylene-80 pipes in LRI zones, continued.

LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	3	0.077	-	-	-	-
25	9	0.038	-	-	-	-
32	89	0.913	-	-	-	-
50	461	17.456	4	0.304	4	0.2
63	1618	30.560	7	0.410	7	0.2
100	4	0.014	-	-	-	-
200	1	0.000	-	-	-	-
250	2	0.030	-	-	-	-
Total	**2187**	**49.087**	**11**	**0.713**	**11**	**0.2**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	4	0.057	-	-	-	-
25	31	0.225	1	0.066	1	4.4
32	144	1.544	-	-	-	-
50	1324	47.748	22	1.470	24	0.5
63	4114	75.019	43	3.724	46	0.6
65	3	0.093	-	-	-	-
75	4	0.005	-	-	-	-
100	2	0.065	-	-	-	-
150	2	0.001	-	-	-	-
Total	**5628**	**124.755**	**66**	**5.260**	**71**	**0.6**

M-Lined Ductile Iron pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
-	-	-	-	-	-	-
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	2	0.012	-	-	-	-
200	5	0.109	-	-	-	-
300	33	0.889	-	-	-	-
Total	**40**	**1.009**	**-**	**-**	**-**	**-**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
300	6	0.2473	-	-	-	-
Total	**6**	**0.2473**	**-**	**-**	**-**	**-**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
200	28	0.727	1	0.012	1	1.4
300	3	0.071	-	-	-	-
Total	**31**	**0.797**	**1**	**0.012**	**1**	**1.3**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
300	3	0.038	-	-	-	-
Total	**3**	**0.038**	**-**	**-**	**-**	**-**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
200	4	0.043	-	-	-	-
300	5	0.206	-	-	-	-
Total	**9**	**0.250**	**-**	**-**	**-**	**-**

Concrete-Lined Ductile Iron pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
-	-	-	-	-	-	-
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	6	0.046	1	0.029	1	21.8
150	4	0.131	-	-	-	-
200	7	0.100	-	-	-	-
300	13	0.572	-	-	-	-
Total	**30**	**0.850**	**1**	**0.029**	**1**	**1.2**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
150	8	0.212	-	-	-	-
200	9	0.088	-	-	-	-
225	1	0.000	-	-	-	-
300	1	0.206	-	-	-	-
Total	**19**	**0.506**	**-**	**-**	**-**	**-**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	7	0.101	-	-	-	-
150	47	0.836	1	0.073	1	1.2
200	39	0.633	-	-	-	-
300	18	0.466	-	-	-	-
Total	**111**	**2.037**	**1**	**0.073**	**1**	**0.5**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	8	0.036	-	-	-	-
150	4	0.028	-	-	-	-
200	45	1.813	-	-	-	-
Total	**57**	**1.877**	**-**	**-**	**-**	**-**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	5	0.015	-	-	-	-
150	4	0.096	-	-	-	-
200	24	0.645	-	-	-	-
300	25	1.206	-	-	-	-
Total	**58**	**1.962**	**-**	**-**	**-**	**-**

M-PVC pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	16	0.424	5	0.307	6	14.2
150	15	0.749	-	-	-	-
200	1	0.050	-	-	-	-
Total	**32**	**1.223**	**5**	**0.307**	**6**	**4.9**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	155	4.848	2	0.141	2	0.4
150	56	1.785	3	0.171	3	1.7
200	46	1.584	3	0.113	4	2.5
Total	**257**	**8.217**	**8**	**0.426**	**9**	**1.1**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	306	8.593	2	0.148	2	0.2
150	202	6.741	1	0.121	1	0.1
200	71	2.375	1	0.068	1	0.4
300	10	0.201	-	-	-	-
Total	**589**	**17.911**	**4**	**0.337**	**4**	**0.2**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
50	2	0.016	-	-	-	-
100	405	8.934	2	0.065	2	0.2
150	250	9.137	-	-	-	-
200	181	6.414	-	-	-	-
300	23	1.844	-	-	-	-
Total	**861**	**26.345**	**2**	**0.065**	**2**	**0.002**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length km)**	**Total Repairs (n)**	**Repairs/ km**
63	3	0.046	-	-	-	-
75	1	0.030	-	-	-	-
100	87	1.558	-	-	-	-
150	79	2.963	-	-	-	-
200	255	8.957	-	-	-	-
300	31	1.771	-	-	-	-
Total	**1493**	**50.481**	-	-	-	-

Continued next page

M-Polyvinyl Chloride pipes in LRI zones, continued

No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
63	2	0.087	-	-	-	-
75	1	0.001	-	-	-	-
100	584	15.345	2	0.123	2	0.1
150	543	18.461	1	0.018	1	0.1
200	274	12.375	2	0.285	2	0.2
300	89	4.213	-	-	-	-
Total	**1493**	**50.481**	**5**	**0.426**	**5**	**0.1**

Unplasticised Polyvinyl Chloride pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	17	0.769	1	0.055	2	2.602
150	15	0.883	-	-	-	-
200	21	0.689	1	0.125	3	4.352
Total	**53**	**2.341**	**2**	**0.180**	**5**	**2.136**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	73	2.266	1	0.056	1	0.4
150	35	1.209	-	-	-	-
200	10	0.275	1	0.055	1	3.6
300	5	0.183	-	-	-	-
Total	**123**	**3.932**	**2**	**0.111**	**2**	**0.5**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	138	3.783	1	0.097	1	0.3
150	112	3.447	1	0.057	1	0.3
200	26	0.815	-	-	-	-
300	33	0.857	-	-	-	-
Total	**309**	**8.901**	**2**	**0.154**	**2**	**0.2**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
63	4	0.015	-	-	-	-
100	205	4.998	-	-	-	-
150	140	3.534	-	-	-	-
200	71	1.948	-	-	-	-
250	2	0.006	-	-	-	-
300	48	1.136	1	0.296	2	1.8
Total	**470**	**11.636**	**1**	**0.296**	**2**	**0.2**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
63	6	0.095	-	-	-	-
100	150	3.765	-	-	-	-
150	157	5.355	-	-	-	-
200	116	3.723	1	0.131	1	0.3
300	300	1.773	-	-	-	-
Total	**729**	**14.710**	**1**	**0.131**	**1**	**0.1**

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Unplasticised Polyvinyl Chloride pipes in LRI zones, continued.

No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
63	2	0.005	-	-	-	-
100	370	9.999	4	0.597	4	0.4
150	290	10.809	5	0.407	9	0.8
200	189	6.455	-	-	-	-
300	40	1.988	-	-	-	-
375	17	1.137	1	0.470	1	0.9
Total	**908**	**30.394**	**10**	**1.474**	**14**	**0.5**

Ductile Iron pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	12	0.125	2	0.078	2	16.0
300	11	0.596	4	0.320	6	10.1
Total	**23**	**0.721**	**6**	**0.398**	**8**	**11.1**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	56	0.532	2	0.119	2	3.8
125	2	0.007	-	-	-	-
150	50	0.737	2	0.044	2	2.7
200	203	4.339	9	0.533	12	2.8
250	1	0.003	-	-	-	-
300	29	1.557	3	0.558	5	3.2
400	1	0.006	-	-	-	-
Total	**342**	**7.182**	**16**	**1.254**	**21**	**2.9**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	33	0.385	1	0.011	1	2.6
150	53	1.265	-	-	-	-
200	111	3.332	1	0.041	1	0.3
250	3	0.003	-	-	-	-
300	90	3.287	3	0.260	4	1.2
375	2	0.275	-	-	-	-
450	10	0.105	-	-	-	-
Total	**302**	**8.653**	**5**	**0.312**	**6**	**0.7**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	88	0.774	1	0.011	2	2.6
150	178	3.624	1	0.033	1	0.3
200	336	5.878	2	0.044	2	0.3
250	4	0.024	-	-	-	-
300	155	3.961	-	-	-	-
375	8	0.260	-	-	-	-
Total	**769**	**14.520**	**4**	**0.088**	**5**	**0.3**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	1	0.006	-	-	-	-
150	9	0.220	-	-	-	-
200	31	0.691	-	-	-	-
300	15	0.101	-	-	-	-
375	2	0.020	-	-	-	-
Total	**58**	**1.038**	-	-	-	-

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Ductile Iron pipes in LRI zones, continued.

No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	34	0.252	-	-	-	-
125	1	0.001	-	-	-	-
150	81	1.407	-	-	-	-
200	136	1.866	1	0.040	1	0.5
225	5	0.026	-	-	-	-
250	18	0.095	-	-	-	-
300	166	6.760	1	0.120	2	0.3
Total	**441**	**10.407**	**2**	**0.160**	**3**	**0.3**

High-Density Polyethylene pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
25	277	8.207	45	1.972	58	7.1
40	297	14.453	37	2.635	46	3.2
50	459	3.174	21	0.607	24	7.6
Total	**1033**	**25.833**	**103**	**5.215**	**128**	**5.0**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	17	0.334	1	0.061	3	9.0
25	1110	31.157	82	3.630	102	3.3
38	3	0.199	-	-	-	-
40	1540	71.226	128	9.129	164	2.3
50	2330	16.374	62	1.812	77	4.7
Total	**5000**	**119.291**	**273**	**14.631**	**346**	**2.9**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
13	3	0.041	-	-	-	-
20	45	0.929	4	0.221	8	8.6
25	1399	42.339	79	3.362	105	2.5
32	4	0.075	2	0.056	2	26.8
38	8	0.416	3	0.306	3	7.2
40	1819	79.535	103	6.600	130	1.6
50	2974	37.664	68	4.046	99	2.6
Total	**6252**	**160.997**	**259**	**14.592**	**347**	**2.2**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
13	17	0.351	-	-	-	-
15	3	0.009	-	-	-	-
20	97	2.022	3	0.081	1	0.5
25	1801	49.199	77	3.296	94	1.9
32	1	0.013	-	-	-	-
38	14	0.901	2	0.236	3	3.3
40	2965	130.996	181	12.483	246	1.9
50	4785	60.315	100	4.030	122	2.0
63	2	0.001	-	-	-	-
Total	**9685**	**243.806**	**363**	**20.127**	**466**	**1.9**

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High-Density Polyethylene pipes in LRI zones, continued.

LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
13	40	1.071	-	-	-	-
15	8	0.129	-	-	-	-
20	162	3.112	2	0.039	2	0.6
25	802	17.001	6	0.220	6	0.4
32	301	3.501	4	0.081	4	1.1
38	42	1.098	-	-	-	-
40	787	22.228	11	0.950	17	0.8
50	2186	59.031	30	2.549	32	0.5
63	2	0.027	-	-	-	-
Total	**4330**	**107.199**	**53**	**3.840**	**61**	**0.6**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
13	1	0.014	-	-	-	-
15	2	0.014	-	-	-	-
20	114	1.541	1	0.014	1	0.6
25	992	23.972	30	1.335	33	1.4
32	140	1.094	-	-	-	-
38	17	0.707	4	0.221	4	5.7
40	1888	71.449	81	5.919	89	1.2
50	3884	86.711	99	7.572	107	1.2
Total	**7038**	**185.502**	**215**	**15.060**	**234**	**1.3**

Polyvinyl Chloride pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	104	4.000	25	1.862	55	13.8
150	59	2.308	5	0.386	5	2.2
200	21	0.684	1	0.046	1	1.5
300	4	0.208	0	0.000	0	0.0
Total	**188**	**7.200**	**31**	**2.294**	**61**	**8.5**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
25	48	1.496	2	0.097	2	1.3
38	1	0.088	1	0.088	1	11.3
40	31	2.282	2	0.174	3	1.3
50	32	0.154	-	-	-	-
80	1	0.001	-	-	-	-
100	472	14.423	18	1.847	22	1.5
150	259	8.383	7	0.517	9	1.1
200	60	1.643	-	-	-	-
300	39	1.495	4	0.409	4	2.7
Total	**943**	**29.964**	**34**	**3.133**	**41**	**1.4**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
25	31	0.415	-	-	-	-
32	45	0.456	-	-	-	-
40	51	1.519	3	0.289	3	2.0
50	106	1.692	3	0.220	3	1.8
75	1	0.001	-	-	-	-
80	25	0.156	-	-	-	-
100	462	12.675	3	0.270	3	0.2
150	290	11.034	14	0.949	15	1.4
200	140	4.391	2	0.034	2	0.5
300	54	3.112	1	0.388	1	0.3
375	2	0.001	-	-	-	-
Total	**1207**	**35.451**	**26**	**2.150**	**27**	**0.8**

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Polyvinyl Chloride pipes in LRI zones, continued.

LRI 3						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
15	30	0.085	-	-	-	-
20	17	0.121	-	-	-	-
25	272	7.653	4	0.192	4	0.5
32	125	1.329	-	-	-	-
38	20	0.564	-	-	-	-
40	445	13.749	-	-	-	-
50	956	21.459	1	0.017	1	0.0
75	7	0.540	-	-	-	-
80	127	1.328	-	-	-	-
100	2438	67.624	4	0.405	4	0.1
150	1608	52.203	4	0.203	4	0.1
200	885	34.333	3	0.276	4	0.1
225	6	0.270	-	-	-	-
250	2	0.014	-	-	-	-
300	451	24.502	1	0.224	2	0.1
375	25	0.346	-	-	-	-
450	1	0.002	-	-	-	-
600	2	0.002	-	-	-	-
Total	**7417**	**226.124**	**17**	**1.318**	**19**	**0.1**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
15	1	0.009	-	-	-	-
20	14	0.088	-	-	-	-
25	63	1.258	-	-	-	-
32	45	0.487	-	-	-	-
38	16	0.457	-	-	-	-
40	105	2.030	1	0.025	1	0.5
50	385	11.428	5	0.657	5	0.4
75	6	0.539	1	0.479	1	1.9
80	58	0.582	-	-	-	-
100	163	3.736	1	0.043	1	0.3
150	173	6.039	1	0.074	1	0.2
200	120	6.609	-	-	-	-
300	129	8.466	2	1.893	2	0.2
Total	**1278**	**41.728**	**11**	**3.171**	**11**	**0.3**

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Polyvinyl Chloride pipes in LRI zones, continued.

No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	1	0.021	-	-	-	-
25	88	2.780	4	0.169	4	1.4
32	22	0.165	1	0.012	2	12.1
38	2	0.011	-	-	-	-
40	162	4.374	3	0.209	3	0.7
50	318	6.342	7	0.250	7	1.1
80	18	0.270	-	-	-	-
100	528	14.711	1	0.053	1	0.1
150	318	9.492	2	0.421	2	0.2
200	302	14.034	7	1.162	7	0.5
225	6	0.270	-	-	-	-
250	2	0.014	-	-	-	-
300	149	7.540	-	-	-	-
375	23	0.344	-	-	-	-
600	2	0.002	-	-	-	-
Total	**1941**	**60.370**	**18**	**2.276**	**26**	**0.4**

Concrete-Lined Steel pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	30	1.187	11	0.710	22	18.5
Total	**30**	**1.187**	**11**	**0.710**	**22**	**18.5**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	157	5.274	36	2.349	78	14.8
150	27	0.572	6	0.327	13	22.7
200	49	1.067	2	0.057	2	1.9
250	10	0.129	1	0.048	1	7.8
300	72	3.190	4	0.274	6	1.9
375	25	1.166	1	0.072	2	1.7
600	14	1.383	2	0.460	2	1.4
Total	**354**	**12.781**	**52**	**3.587**	**104**	**8.1**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	25	0.706	2	0.204	2	2.8
150	7	0.353	-	-	-	-
200	49	0.434	-	-	-	-
225	17	0.064	-	-	-	-
250	9	0.566	1	0.510	1	1.8
300	63	1.661	1	0.047	1	0.6
375	19	0.597	3	0.144	3	5.0
450	12	0.207	-	-	-	-
600	6	1.409	-	-	-	-
Total	**207**	**5.996**	**7**	**0.905**	**7**	**1.2**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
75	2	0.002	-	-	-	-
100	54	1.892	5	0.490	6	3.2
150	25	0.510	1	0.016	1	2.0
200	110	1.237	-	-	-	-
225	5	0.005	-	-	-	-
250	9	0.573	-	-	-	-
300	277	6.078	2	0.022	2	0.3
375	23	0.808	-	-	-	-
425	1	0.016	-	-	-	-
450	25	1.726	-	-	-	-
600	5	0.180	1	0.156	1	5.5
Total	**536**	**13.026**	**9**	**0.684**	**10**	**0.8**

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Concrete-Lined Steel pipes in LRI zones, continued.

LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	5	0.037	-	-	-	-
200	3	0.005	-	-	-	-
300	16	0.901	-	-	-	-
450	6	1.002	-	-	-	-
Total	**30**	**1.945**	**-**	**-**	**-**	**-**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	27	0.414	2	0.176	3	7.2
150	15	0.828	-	-	-	-
200	126	1.619	3	0.233	3	1.9
250	16	0.729	3	0.208	3	4.1
300	103	4.637	4	0.690	4	0.9
375	10	2.392	2	1.136	3	1.3
450	21	2.995	2	0.678	2	0.7
600	3	0.193	-	-	-	-
Total	**321**	**13.808**	**16**	**3.122**	**18**	**1.3**

Asbestos Cement pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
50	6	0.120	2	0.078	4	33.5
100	352	11.871	89	5.155	159	13.4
150	127	4.595	34	2.469	63	13.7
200	28	1.325	17	0.844	24	18.1
300	3	0.039	-	-	-	-
Total	**516**	**17.949**	**142**	**8.546**	**250**	**13.9**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
75	1	0.001	-	-	-	-
100	1151	37.670	205	13.040	343	9.1
150	486	16.572	73	4.515	104	6.3
200	277	7.661	29	1.914	48	6.3
225	21	1.002	10	0.427	14	225
250	2	0.001	-	-	-	-
300	172	7.055	11	1.366	16	2.3
Total	**2110**	**69.963**	**328**	**21.262**	**525**	**7.5**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
25	3	0.020	-	-	-	-
40	2	0.043	-	-	-	-
50	14	0.332	2	0.078	4	12.0
75	7	0.113	-	-	-	-
100	1691	58.970	89	5.155	159	2.7
150	748	28.606	34	2.469	63	2.2
200	460	14.132	17	0.844	24	1.7
225	2	0.213	-	-	-	-
250	5	0.051	-	-	-	-
300	222	9.065	-	-	-	-
375	2	0.095	-	-	-	-
Total	**3156**	**111.639**	**142**	**8.546**	**250**	**2.2**

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Asbestos Cement pipes in LRI zones.

LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
25	1	0.028	-	-	-	-
50	38	1.722	1	0.511	3	1.7
75	8	0.175	-	-	-	-
100	2515	85.409	148	10.243	230	2.7
150	1339	45.963	62	4.424	79	1.7
200	871	29.289	37	2.399	50	1.7
225	24	0.612	1	0.082	1	1.6
250	11	0.202	1	0.022	1	5.0
300	366	13.362	2	0.542	2	0.1
375	16	0.582	1	0.011	1	1.7
Total	**5189**	**177.343**	**253**	**18.234**	**367**	**2.1**
LRI 4						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
50	157	7.568	7	0.742	7	0.9
75	16	0.362	-	-	-	-
100	2107	74.079	30	2.552	37	0.5
150	1399	59.347	23	2.299	26	0.4
200	665	30.000	7	0.371	7	0.2
225	15	0.634	-	-	-	-
250	24	2.607	-	-	-	-
300	142	6.808	1	0.082	2	0.3
375	44	3.221	-	-	-	-
400	61	1.231	-	-	-	-
600	6	0.038	-	-	-	-
Total	**4636**	**185.894**	**68**	**6.047**	**79**	**0.4**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
40	4	0.093	-	-	-	-
50	123	5.041	3	0.750	3	0.6
75	24	1.142	2	0.207	2	1.8
80	2	0.069	-	-	-	-
100	2738	96.747	102	7.532	148	1.5
150	1574	63.227	48	4.309	57	0.9
200	728	31.066	30	3.483	34	1.1
225	9	0.410	3	0.843	3	7.3
250	134	5.419	5	0.799	5	0.9
300	180	10.715	11	3.171	20	1.9
375	36	2.183	2	0.524	4	1.8
Total	**5552**	**216.113**	**206**	**21.618**	**276**	**1.3**

Steel pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	4	0.004	-	-	-	-
200	3	0.009	-	-	-	-
Total	**7**	**0.013**	-	-	-	-
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	62	23.660	21	1.505	30	1.3
150	42	13.667	7	0.760	12	0.9
200	10	0.104	-	-	-	-
300	24	0.937	1	0.036	1	1.1
Total	**138**	**38.368**	**29**	**2.301**	**43**	**1.1**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
75	2	0.009	-	-	-	-
100	76	2.557	6	0.323	6	2.3
150	50	0.696	3	0.152	4	5.7
200	35	0.317	1	0.201	1	3.2
250	3	0.010	-	-	-	-
300	25	0.176	-	-	-	-
375	6	0.374	1	0.279	1	2.7
450	3	0.301	-	-	-	-
550	4	0.967	-	-	-	-
600	3	0.230	1	0.005	1	4.3
Total	**207**	**5.637**	**12**	**0.960**	**13**	**2.3**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
75	1	0.011	-	-	-	-
100	94	2.745	6	0.608	10	3.6
150	41	0.874	4	0.273	5	5.7
200	56	0.098	-	-	-	-
250	10	0.311	3	0.174	3	9.6
300	50	0.458	-	-	-	-
375	4	0.055	-	-	-	-
425	2	0.224	-	-	-	-
450	1	0.148	-	-	-	-
600	15	0.554	-	-	-	-
Total	**274**	**5.478**	**13**	**1.055**	**18**	**3.3**

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Steel pipes in LRI zones, continued.

LRI 4						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
75	1	0.000	-	-	-	-
150	3	0.004	-	-	-	-
200	16	0.038	-	-	-	-
250	4	0.005	-	-	-	-
300	17	0.094	-	-	-	-
375	15	1.941	1	0.091	1	0.5
450	4	1.138	-	-	-	-
Total	**60**	**3.221**	**1**	**0.091**	**1**	**0.3**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
100	59	1.473	7	0.638	10	6.8
150	27	0.811	3	0.168	3	3.7
200	27	0.144	-	-	-	-
250	2	0.002	-	-	-	-
300	35	0.285	-	-	-	-
375	4	0.021	-	-	-	-
450	3	0.128	-	-	-	-
550	16	3.297	-	-	-	-
600	7	0.234	-	-	-	-
Total	**180**	**6.392**	**10**	**0.806**	**13**	**2.0**

Galvanised Iron pipes in LRI zones.

LRI 0						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	239	5.913	92	3.703	159	26.9
25	238	1.150	15	0.233	18	15.7
40	10	0.140	3	0.084	5	35.8
50	48	0.337	5	0.085	6	17.8
Total	**535**	**7.540**	**115**	**4.105**	**188**	**24.9**
LRI 1						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	974	17.588	206	6.818	282	16.0
25	879	4.707	45	1.160	56	11.9
32	1	0.001	-	-	-	-
38	3	0.064	-	-	-	-
40	55	1.204	7	0.786	23	19.1
50	406	3.437	29	0.877	32	9.3
Total	**2318**	**27.000**	**287**	**9.641**	**393**	**14.6**
LRI 2						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
20	1158	21.683	200	7.386	289	13.3
25	1176	7.706	55	1.460	74	9.6
32	10	0.358	3	0.251	3	8.4
40	107	2.078	12	0.539	18	8.7
50	611	3.458	26	0.339	28	8.1
100	1	0.001	-	-	-	-
200	1	0.005	-	-	-	-
Total	**3064**	**35.288**	**296**	**9.975**	**412**	**11.7**
LRI 3						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
13	3	0.0599	1	0.058	1	16.7
15	3	0.0461	-	-	-	-
20	1530	27.3126	154	6.098	194	7.1
25	1351	8.7773	34	1.001	45	5.1
32	13	0.3824	2	0.157	2	5.2
38	18	0.4345	1	0.016	1	2.3
40	121	2.8086	12	0.838	17	6.1
50	779	5.0107	23	0.486	27	5.4
75	1	0.0079	-	-	-	-
80	2	0.0083	-	-	-	-
100	4	0.0191	-	-	-	-
150	5	0.1277	-	-	-	-
200	5	0.0214	-	-	-	-
300	1	0.002	-	-	-	-
Total	**3836**	**45.019**	**227**	**8.655**	**287**	**6.4**

Continued next page

Galvanised Iron pipes in LRI zones, continued.

LRI 4						
Diameter (mm)	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs/ km
13	1	0.004				
20	81	1.626	1.000	0.005	1	0.6
25	341	4.592	3.000	0.121	3	0.7
32	35	0.535	-	-	-	-
38	21	0.711	-	-	-	-
40	22	0.707	-	-	-	-
50	54	1.020	2.000	0.138	2	2.0
75	3	0.073	-	-	-	-
100	15	0.757	-	-	-	-
150	1	0.022	-	-	-	-
200	10	0.015	-	-	-	-
Total	**584**	**10.061**	**6**	**0.263**	**6**	**0.6**
No Liquefaction Observations						
Diameter (mm)	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs/ km**
13	2	0.041	-	-	-	-
15	6	0.050	2	0.010	3	59.9
20	461	9.070	54	2.191	73	8.0
25	772	7.402	21	0.645	24	3.2
32	56	1.014	2	0.210	11	10.8
38	7	0.116	-	-	-	-
40	95	2.269	5	0.161	6	2.6
50	461	5.683	18	0.857	30	5.3
65	8	0.058	-	-	-	-
75	33	0.553	-	-	-	-
100	3	0.026	-	-	-	-
150	55	0.868	-	-	-	-
200	5	0.019	-	-	-	-
Total	**1964**	**27.170**	**102**	**4.076**	**147**	**5.4**

Appendix F - Categories of damage information derived from repair records across Christchurch City and Banks Peninsula in the period 5 September 2010 to 30 June 2012

Pipe Material	Total		Pipe Damage		Fitting Damage		Predominant Fitting Composition	No Damage Information	
	(n)	(%)	(n)	%	n	%		n	%
MPVC	27	0.4	8	30	3	11	CI, DI	16	59
PVC	190	3	33	17	50	26	CI, DI	107	56
MDPE80	257	4	19	7	147	57	Plastic	91	35
DI	49	1	2	4	19	39	DI	28	57
HDPE	1261	21	140	11	587	47	Plastic	534	42
AC	1816	30	606	33	461	25	CI	749	41
S	84	1	17	20	29	35	CI	38	45
CI	574	9	73	13	244	43	CI	257	45
CLS	144	2	19	13	80	56	CI, DI	45	31
GI	1692	28	347	21	538	32	GI	807	48
Total	**6094**	**100**	**1264**	**21**	**2158**	**35**		**2672**	**44**

Appendix G - Pipe Materials Modes of Failure

The following data all cover the period 4 September 2010 to 30 June 2012.

(red)	No Information
(light grey)	Fitting
(light blue)	Pipe

High-Density Polyethylene

Damage Category	N	%
No Information	529	47
Fitting - Unspecified	154	14
Fitting - Coupler	134	12
Fitting - Property Connection	94	8
Pipe - Longitudinal Split	67	6
Pipe - Unspecified Break	26	2
Fitting - Endcap	23	2
Fitting - Tee	22	2
Fitting - Elbow	19	2
Fitting - Pipe Connection	17	2
Pipe - Pinhole	12	1
Fitting - Bend	10	1
Fitting - Gate Valve	7	1
Total	**1114**	**100**

Asbestos Cement

Damage Category	N	%
Unspecified Fault	1014	56.1
Pipe - Collar	102	5.6
Fitting - Gibault	101	5.6
Pipe - Broken Back	96	5.3
Pipe - Cracked	67	3.7
Pipe - Longitudinal Split	66	3.7
Pipe - Unspecified Break	66	3.7
Fitting - Coupler	62	3.4
Fitting - Pipe Connection	59	3.3
Pipe - Blown	36	2.0
Pipe - Circumferential Split	35	1.9
Fitting - Previous Repair	28	1.5
Fitting - Unspecified	16	0.9
Fitting - Joint	9	0.5
Pipe - Unspecified Break at Fitting	8	0.4
Fitting - Tee	7	0.4
Pipe - Snapped	6	0.3
Fitting - Sluice Valve	5	0.3
Pipe - Misalignment	4	0.2
Fitting - Endcap	3	0.2
Fitting - Valve	3	0.2
Pipe - Pinhole	3	0.2
Fitting - Gate Valve	2	0.1
Pipe - Blown at Fitting	2	0.1
Pipe - Impacted	2	0.1
Fitting - Bend	1	0.1
Fitting - Flange Adaptor	1	0.1
Fitting - Hydrant	1	0.1
Fitting - Socket	1	0.1
Fitting - Tee Impacted by Pipe	1	0.1
Pipe - Circumferential Split at Fitting	1	0.1
Total	**1808**	**100**

(red)	No Information
(light grey)	Fitting
(light blue)	Pipe

Medium-Density Polyethylene 80

Damage Category	N	%
Unspecified Fault	102	41.6
Fitting - Property Connection	66	26.9
Fitting - Unspecified	17	6.9
Fitting - Coupler	11	4.5
Fitting - Tee	11	4.5
Fitting - Pipe Connection	10	4.1
Pipe - Unspecified Break	9	3.7
Fitting - Elbow	5	2.0
Pipe - Pinhole	4	1.6
Fitting - Endcap	2	0.8
Fitting - Previous Repair	2	0.8
Pipe - Longitudinal Split	2	0.8
Fitting - Gate Valve	1	0.4
Fitting - Gibault	1	0.4
Fitting - Sluice Valve Box	1	0.4
Fitting - Toby Box	1	0.4
Total	**245**	**100**

Polyvinyl Chloride

Damage Category	N	%
Unspecified Fault	73	53
Fitting - Coupler	14	10
Pipe - Collar	14	10
Fitting - Gibault	8	6
Pipe - Longitudinal Split	6	4
Fitting - Unspecified	5	4
Fitting - Property Connection	3	2
Pipe - Blown	3	2
Pipe - Unspecified Break	3	2
Fitting - Previous Repair	2	1
Fitting - Pipe Connection	2	1
Fitting - Tee	2	1
Fitting - Endcap	1	1
Fitting - Gate Valve	1	1
Fitting - Valve	1	1
Pipe - Unspecified Break at Collar	1	1
Total	**139**	**100**

(red)	No Information
(light grey)	Fitting
(light blue)	Pipe

Cast Iron

Damage Category	N	%
Unspecified Fault	253	45.2
Fitting - Lead Joint	112	20.0
Fitting - Collar	50	8.9
Fitting - Gibault	23	4.1
Pipe - Blown	20	3.6
Pipe - Broken Back	19	3.4
Fitting - Pipe Connection	17	3.0
Fitting - Previous Repair	14	2.5
Pipe - Longitudinal Split	9	1.6
Fitting - Coupler	8	1.4
Fitting - Tee	7	1.3
Pipe - Cracked	7	1.3
Fitting - Unspecified	4	0.7
Pipe - Unspecified Break	4	0.7
Pipe - Circumferential Split	3	0.5
Pipe - Bell Join	2	0.4
Fitting - Bend	1	0.2
Fitting - Endcap	1	0.2
Fitting - Flange	1	0.2
Fitting - Gate Valve	1	0.2
Fitting - Sluice Valve	1	0.2
Fitting - Socket	1	0.2
Pipe - Pinhole	1	0.2
Pipe - Thrust Block	1	0.2
Total	**560**	**100**

Galvanised Iron

Damage Category	N	%
Unspecified Fault	954	60.2
Fitting - Coupler	109	6.9
Fitting - Tee	94	5.9
Pipe - Pinhole	66	4.2
Pipe - Unspecified Break	59	3.7
Fitting - Unspecified	57	3.6
Pipe - Blown	51	3.2
Pipe - Longitudinal Split	45	2.8
Fitting - Bend	41	2.6
Fitting - Property Connection	18	1.1
Fitting - Previous Repair	16	1.0
Pipe - Unspecified Break, Corrosion	15	0.9
Fitting - Pipe Connection	14	0.9
Pipe - Cracked	9	0.6
Fitting - Valve	8	0.5
Pipe - Pitted	8	0.5
Fitting - Gate Valve	7	0.4
Pipe - Snapped	3	0.2
Pipe - Corrosion	2	0.1
Fitting - Bend & Tee	1	0.1
Fitting - Bend, Corroded	1	0.1
Fitting - Coupler & Bend	1	0.1
Fitting - Endcap	1	0.1
Fitting - Gibault	1	0.1
Pipe - Circumferential Split	1	0.1
Pipe - Impacted	1	0.1
Pipe - Kinked	1	0.1
Pipe - Longitudinal Split, Corrosion	1	0.1
Total	**1585**	**100**

Appendix H – Summary performance data for waste water materials.

Pipe Material	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
CONC	14108	795.878	624	43.088	762	1.0
EW	6924	389.511	485	34.936	593	1.5
UPVC	7984	372.188	47	2.545	53	0.1
AC	3513	179.021	79	6.104	119	0.7
PVC	1267	54.122	8	0.309	9	0.2
MPVC	250	22.304	-	-	-	-
HDPE	1360	22.282	6	0.433	8	0.4
CI	764	20.116	10	0.863	13	0.6
GI	1121	8.733	-	-	-	-
MDPE80	120	6.914	1	0.108	1	0.1
PE	110	6.22	-	-	-	-
BB	92	5.948	4	0.426	4	0.7
LDPE	90	2.09	-	-	-	-
DI	147	0.404	-	-	-	-
S	58	0.223	1	0.037	1	4.5
Total	**37908**	**1885.953**	**1265**	**88.849**	**1563**	**0.8**

Appendix I – Summary performance data for waste water materials according to Liquefaction Resistance Index Zone.

Unplasticised Polyvinyl Chloride						
LRI Zone	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs km^{-1}**
0	172	8.371	16	0.785	17	2.0
1	351	16.276	3	0.158	3	0.2
2	681	36.665	11	0.701	15	0.4
3	1121	56.795	1	0.086	2	0.04
4	873	41.771	-	-	-	-
No Obs	1917	105.450	5	0.171	5	0.05
Total	**5115**	**265.329**	**36**	**1.901**	**42**	**0.2**

Medium Density Polyethylene 80						
LRI Zone	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs km^{-1}**
0	-	-	-	-	-	-
1	6	0.472	1	0.108	1	2.1
2	4	0.299	-	-	-	-
3	11	0.518	-	-	-	-
4	5	0.195	-	-	-	-
No Obs	54	2.697	-	-	-	-
Total	**80**	**4.182**	**1**	**0.108**	**1**	**0.2**

Polyvinyl Chloride						
LRI Zone	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs km^{-1}**
0	15	0.168	1	0.003	1	5.9
1	40	2.556	1	0.006	1	0.4
2	140	4.502	1	0.042	1	0.2
3	186	8.859	1	0.08	1	0.1
4	42	1.861				
No Obs	212	9.911	1	0.094	1	0.1
Total	**635**	**27.857**	**5**	**0.225**	**5**	**0.2**

High-Density Polyethylene						
LRI Zone	**Total Pipes (n)**	**Total Length (km)**	**Repaired Pipes (n)**	**Affected Length (km)**	**Total Repairs (n)**	**Repairs km^{-1}**
0	38	0.298	1	0.099	1	3.4
1	157	2.291	1	0.077	1	0.4
2	171	1.336	1	0.081	2	1.5
3	296	4.096	2	0.119	2	0.5
4	139	0.623				
No Obs	316	3.770				
Total	**1117**	**12.355**	**5**	**0.376**	**6**	**0.5**

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Asbestos Cement						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	70	3.393	17	1.048	17	5.0
1	174	8.805	11	0.860	19	2.2
2	383	22.692	15	1.723	23	1.0
3	493	21.443	7	1.169	7	0.3
4	612	30.313				
No Obs	797	46.459	4	0.212	6	0.1
Total	**2529**	**133.105**	**54**	**5.012**	**72**	**0.5**

Brick Barrell						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	1	0.103	1	0.103	1	9.7
1	46	2.702	3	0.323	3	1.1
2	10	1.074				
3	25	1.508				
4						
No Obs	10	0.561				
Total	**92**	**5.948**	**4**	**0.426**	**4**	**0.7**

Reinforced Concrete Rubber Ring Jointed						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	460	24.752	138	8.845	167	6.7
1	1106	63.521	80	5.555	106	1.7
2	1552	88.877	151	10.380	197	2.2
3	2490	138.057	80	5.572	98	0.7
4	2461	141.962	1	0.060	1	0.01
No Obs	3139	179.173	30	2.173	32	0.2
Total	**11208**	**636.340**	**480**	**32.585**	**601**	**0.9**

Concrete						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	60	2.837	13	0.912	13	4.6
1	524	30.367	38	3.178	45	1.5
2	334	21.458	22	1.932	24	1.1
3	545	33.304	28	1.987	29	0.9
4	67	3.734				
No Obs	504	32.187	10	0.865	12	0.4
Total	**2034**	**123.887**	**111**	**8.874**	**123**	**1.0**

Earthenware						
LRI Zone	Total Pipes (n)	Total Length (km)	Repaired Pipes (n)	Affected Length (km)	Total Repairs (n)	Repairs km^{-1}
0	137	6.984	44	2.547	61	8.7
1	1059	63.258	153	11.076	185	2.9
2	1116	71.624	117	9.379	152	2.1
3	1932	120.474	71	5.898	77	0.6
4	221	11.939	2	0.151	2	0.2
No Obs	1092	65.254	44	3.216	57	0.9
Total	**5557**	**339.532**	**431**	**32.267**	**534**	**1.6**

PREDICTING EARTHQUAKE DAMAGE TO GRAVITY PIPE NETWORKS

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ABSTRACT

This paper describes the drivers for and development and application of a GIS and Excel-based Pipe Damage Assessment (PDA) Tool. The PDA Tool was developed by the Stronger Christchurch Infrastructure Rebuild Team to provide a desktop assessment of the condition of wastewater and stormwater pipes after they were damaged by a series of large earthquakes in 2010 and 2011.

By using a multiple-parameter approach it achieved up to 95% accuracy, compared to up to 60% accuracy for a single parameter approach. Outputs were successfully applied to the design of rebuild works, scoping and budgeting, and for prioritisation and estimating.

INTRODUCTION

Christchurch is the largest city in New Zealand's South Island, with a population of about 360,000. It was struck by a series of major earthquakes, which took 185 lives and caused extensive damage to land, property and infrastructure.

SCIRT (Stronger Christchurch Infrastructure Rebuild Team) is responsible for rebuilding horizontal infrastructure in Christchurch following the earthquakes. Ultimately SCIRT is responsible to the people of Christchurch and New Zealand.

SCIRT is made up of local people from many organisations. The head contractual agreement within SCIRT is an alliance between owner participants and non-owner participants. The owner participant organisations are: Canterbury Earthquake Recovery Authority, Christchurch City Council and the New Zealand Transport Agency. The non-owner participant organisations are City Care, Downer, Fletcher, Fulton Hogan and McConnell Dowell. There are also many other Christchurch-based companies, who are part of SCIRT, playing a vital role in delivering the SCIRT programme of work.

As part of the response to the earthquakes, an extensive Closed Circuit Television (CCTV) inspection programme was commenced to identify earthquake damage to the network of more than 1,600km of gravity wastewater and 900km of gravity stormwater pipes, using the New Zealand Pipe Inspection Manual as a methodology, and to define the nature and severity of defects. The cost of collecting CCTV data on all gravity pipes was estimated to be in the order of $125M. Due to the extensive damage and despite having at least 20 CCTV crews in the field (equating to around half of New Zealands specialist CCTV field resource), the estimated time required to complete CCTV survey of the damaged pipes was more than four years. Availability of CCTV data became a critical constraint to the rebuild.

This critical constraint led to the development of a desktop method that could reliably predict CCTV outputs. Its function was to speed up the rebuild process, by providing estimates of damage, based on a range of inputs including CCTV observations from across the city, which were used as a representative sample of the pipe condition. A desktop method called the Pipe Damage Assessment (PDA) Tool was created for this purpose and its development and use is described in this paper.

In committing to support the development of such a tool, SCIRT identified that while the methodology must be sound, the priority was that the development proceeded quickly enough to keep ahead of the design and construction teams, and produced accurate and consistent results.

DEVELOPMENT OF THE TOOL

Initial Development

The idea behind the PDA Tool was relatively simple:
It is not possible to inspect and assess all of the damage to the pipes, due to time and financial constraints. However, there might be a set of relationships between observed damage to the pipes and other things that can be seen and measured. The damage to pipes without observation data could then be predicted by applying these relationships.

Observation data were sourced from CCTV of the wastewater network. CCTV video was assessed and coded in accordance with the New Zealand Pipe Inspection Manual (Water NZ 2011).

A list of 31 indicators was developed, using engineering judgement and experience. These indicators came from a range of sources including:

- Geotechnical Data
- Pipe Asset Data
- Network Performance Data
- Earthquake Data

and a range of miscellaneous sources

The first question was whether the data in the observation data and indicator data sets should be continuous, a mixture of continuous and discrete, or only discrete. Observation data were available as numerical scores (which were continuous) and as recommended outcomes (which were discrete). Damage Indicators could be continuous (e.g. direction), apparently continuous (e.g. diameter) or discrete (e.g. Damage Zone). As some damage indicators, such as suburb, could not be converted to continuous values, it was decided to use a discrete approach and convert continuous data by grouping similar values into bins.

Some indicators were initially eliminated due to:

- Lack of a dataset
- Data not in geospatial format
- Low confidence in data quality

The remaining damage indicators were imported to ESRI Arc10 and assessed, and further eliminations were made due to:

- Incomplete datasets. The indicator data had to completely overlap the pipe data.
- The need for significant geospatial processing, due to time constraints.

Finally, a spatial join was undertaken in GIS to aggregate the indicators and provide a value for each indicator for every pipe that had a CCTV observation, along with the CCTV outcome. The resulting file was exported to Excel. The CCTV outcome could be one of four categories, three of which were used:

- Renewal – The pipeline required renewal between the manholes. This indicates significant damage. The Renewal could involve either full pipe relining or relay with a new pipe between manholes.
- Repair – The pipeline was to be excavated at breaks and either patch repairs made or a patch lining installed.
- No Action – The pipeline was either undamaged, or the damage was minor.
- Abandoned – The CCTV survey had to be abandoned for some reason, such as high flows, obstructions in the pipe and unsafe working conditions for the CCTV crew. This category was not used in the PDA Tool.

Basic statistical tests were completed to determine whether each of the damage indicators has a statistically significant relationship with the CCTV outcome. Where a low correlation was found the indicator was eliminated from further consideration.

Eight damage indicators were not eliminated, and are referred to as "measures". The measures used in the Pipe Damage Assessment Tool are listed in Table 1.

Table 1: Damage Measures

Name	Size	Description
Depth	Five values	The average depth of the pipe.
Diameter	~30 values	The diameter of the pipe.
Direction	16 values	The angle of the pipe, from upstream to downstream, in degrees, with north equal to zero.
Liquefaction Resistance Index (LRI) (Cubrinovski, Hughes et al 2011)	Seven values	A measure of the soil performance under historic and future earthquake loads.
Material	~30 values	The pipe material.
Watercourse Proximity	Seven values	The distance to the closest open watercourse.
Subcatchment	~250 values	The wastewater catchment.
RAMM	Five values	Summarised road condition data.

The values for each measure with CCTV observations available were amalgamated into bins if:

- The number of records with CCTV observations was below a threshold value (25), or

- The percentage of the total number of values with CCTV observations was below a threshold value (5%)

Examples:

1. Earthenware (EW) made up 24% of the length installed. CCTV had been undertaken on 46% of the length, no amalgamation was necessary.
2. PVC was labelled PVC, uPVC and mPVC and had a combined length that made up 21% of the network. uPVC and PVC met both criteria to avoid amalgamation and mPVC did not meet either. All appeared to perform in a similar manner, acknowledging the small size of the dataset available to assess mPVC, and with no other distinguishing features they were all amalgamated into a bin called PVC.
3. Unreinforced Concrete (CONC) and reinforced concrete (RCRR) were initially placed in one bin. Analysis of the year of installation showed a clear phasing out of CONC, followed by the phasing in of RCRR. Further analysis of the CCTV observations showed the material types had performed differently. Bins for each were created and the values were de-amalgamated.

Statistical relationships between the value for each measure and the observed CCTV outcome were then calculated. Table 2 and Figure 1 show the statistical relationships for Watercourse Proximity.

Table 2: Statistical Relationships for Watercourse Proximity.

CCTV Outcome	Distance from Watercourse (m)						
	0 – 25	25 – 50	50 – 75	75 – 100	100 – 150	150 – 200	>200m
No Action (%)	31	31	35	35	32	29	30
Repair (%)	27	30	29	28	27	30	34
Renewal (%)	42	39	36	37	39	41	36

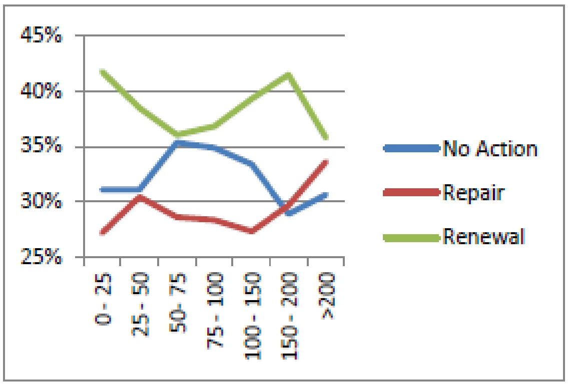

Figure 1: Statistical Relationships for Watercourse Proximity

Weightings for each measure were calculated, based on the ability of the measure to predict the observed CCTV outcome. Higher weightings were allocated to measures that predicted the observed CCTV outcome more often. Individually the eight measures predicted the observed CCTV outcome for between 45% and 60% of the pipes with completed CCTV. Weightings were normalised, so that the sum of the weightings for the measures was always equal to 1.

The preferred action for a pipe was calculated in two stages. First the weighting for each measure was multiplied by the probability of the CCTV outcome, for each of the outcomes. Then, for each outcome the products of weighting and probability were summed. This is expressed mathematically in Equation 1. The outcome with the highest sum was the preferred action. The preferred action became the recommended action, if no observed CCTV outcome was available. For all pipes with a complete CCTV survey the recommended action was sourced from CCTV, irrespective of what the PDA Tool produced as a preferred action.

$$P(outcome) = \sum_{n}^{1} P_{(outcome,measure)} \cdot W_{(measure)} \quad (1)$$

Where:
P is the probability
W is the weighting
n is the number of the measure, from 1 to 8.

Ongoing Development

Once the initial PDA Tool for the wastewater system had been created and shown to be reliable, a PDA Tool for the stormwater system was developed. The principles and format used were identical. However, the statistical relationships and weightings were different to those found for the wastewater system, for a variety of reasons, including:

- Different construction methods, ages, materials, pipe sizes and layouts
- Different assessment criteria for the CCTV observations
- Depth data were not available for stormwater

Approximately 100 Rebuild Areas were identified by SCIRT and prioritised. Practical applications of the PDA Tool required it to be applied at a Rebuild Area level.

The concept of calibrating the outputs was developed based on the need to exclude the Liquefaction Resistance Index (LRI) from some of the Rebuild Areas and the lack of depth data for stormwater assets.

Most of Christchurch is situated on alluvial plains, which are susceptible to liquefaction under earthquake loads. The Port Hills suburbs are built on the remnants of a volcanic cone, and the soils are not susceptible to liquefaction, so including LRI was unnecessary. Based on the trials undertaken it was observed that removing LRI as a measure improved the accuracy of the prediction.

The weightings for the remaining measures needed to be re-normalised, and functionality added to automatically recalculate the weightings.

Trial and error showed that removing other measures could change the number of matches between observed CCTV outcome and predicted outcome, often resulting in fewer matches and sometimes resulting in more matches. A macro was created to check every combination of measures. This macro initially identified the combination that gave the highest number of matches. Subsequently it was modified to identify the combination of measures that gave the greatest length of matches. A calibration table was developed to quantify the accuracy of the calibration, as shown in Tables 3 and 4.

The tables compare the observed CCTV outcome against the outcome predicted by the PDA Tool for all pipes with CCTV observations in the Rebuild Area. The objective of the calibration process was to minimise the length of pipe where the observed CCTV outcome is "No Action" and the PDA Tool predicts either "Repair" or "Renewal" and the length of pipe where the PDA Tool predicts "No Action" and the observed CCTV outcome is either "Repair" or "Renewal". These are shown as the red cells in Tables 3 and 4. The dark green cells show where the observed CCTV outcome and the PDA Tool prediction match. The light green cells show where the observed CCTV outcome and the PDA Tool prediction both favour some form of action; however the nature of the action does not match.

Table 3: Calibration Table (Length)

Length (m)		CCTV			
		Renewal	Repair	No Action	Total
PDA	Renewal	1,788	635	37	2,460
	Repair	1,730	3,250	0	4,980
	No Action	0	0	341	341
	Total	3,518	3,884	378	7,781

Table 4: Sample Calibration Table (Percentage)

Length (%)		CCTV			
		Renewal	Repair	No Action	Total
PDA	Renewal	23%	8%	<1%	32%
	Repair	22%	42%	0%	64%
	No Action	0%	0%	4%	4%
	Total	45%	50%	5%	100%

In the example provided, the PDA Tool has predicted the observed CCTV outcome for 69% of the length of pipes with observation data. The predicted outcome has the incorrect action for a further 30% of the length of pipes with observation data. Less than 1% of the length of pipes with CCTV observations is completely incorrect.

Analysis of the CCTV observations of the stormwater PDA Tool showed that the stormwater network was much less extensively damaged than the wastewater network. The statistical relationships reflected this, and the PDA Tool failed to predict damage correctly on the first Rebuild Areas studied. This was addressed by introducing a Threshold value. When "No Action" was the preferred action and the sum calculated by Equation 1 was below the Threshold, the recommendation for "No Action" was replaced with a recommendation of whichever action ("Repair" or "Renewal") had the highest score. To support this process the macro that identified the best combination of measures was extended to search a range of values for the Threshold.

Further analysis of the balance between Repair and Renewal identified a relationship between the observed CCTV outcome and the length of the pipe, as shown in Figure 2. Once a recommendation to undertake some form of work was made, this relationship was used to adjust which action should be undertaken. It was still possible to predict either outcome; the adjustment only changed the recommendation where an action was recommended and both action outcomes had about the same probability from the initial PDA process.

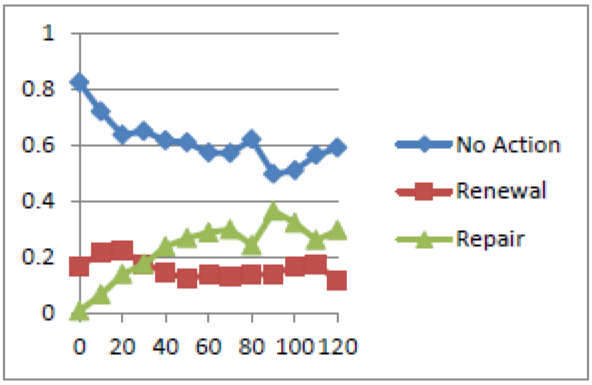

Figure 2: Relationship between Length and Observed CCTV Outcome

When the PDA Tool recommended Repair, this needed to be supported with a prediction of the number of repairs. CCTV observations of pipes that required repairs were used to determine a range of repairs per unit length. The average repair rate was applied by multiplying it by the pipe length, wherever a repair was predicted and the value was rounded up to the nearest whole number. The minimum value was set to one repair.

Refinement

As a separate exercise, SCIRT collected topographical survey data on manhole lid levels, which were used by others within SCIRT to provide a preliminary assessment of whether individual pipes had fallen below minimum allowable grade (Christchurch City Council, 2010). These pipes were identified as requiring Renewal. Pipes that were within 15 years of their replacement age, based on installation year data in the GIS dataset for the pipes, that were located in roads that required reconstruction due to earthquake damage were also identified for Renewal, even where CCTV observations or PDA Tool predictions required No Action. The PDA Tool was upgraded to include these two assessments.

The CCTV programme ran in parallel to the PDA Tool development and application. CCTV records were provided to SCIRT on a daily basis and stored in SCIRT's InfoNet database.

On a monthly basis the CCTV data were updated in the PDA Tool. This involved checking whether any de-amalgamations of bins could be undertaken, updating the statistical relationships and recalculating the weightings. Version control was introduced, to allow the currency of PDA recommendations for Rebuild Areas that had already been studied.

On several occassions CCC and SCIRT made changes to technical standards (Christchurch City Council, 2010) (SCIRT, 2012) that impacted CCTV outcomes in InfoNet. These were incorporated into the PDA Tool as part of the monthly updates with new CCTV data.

When time permitted, the new CCTV records in an updated dataset were used in areas where PDA studies had been undertaken to validate the PDA Tool. This was done by comparing the PDA output with the observed CCTV outcome for pipes where new CCTV observations had been obtained.

USE OF THE TOOL

Once the development of the PDA Tool had been completed it was applied to a range of tasks, to support the process of rebuilding Christchurch

Citywide Network Damage Assessment

Analyses of the complete wastewater and stormwater pipe networks across the city were undertaken to produce a recommended action for all of the 50,000 wastewater pipes and 60,000 stormwater pipes that were within SCIRT's scope of works. The results for individual pipes were aggregated at wastewater subcatchment level and at Rebuild Area level to show the extent of damage and confidence in the recommended outcome.

The level of confidence was calculated using the quantity of completed CCTV and the quality of the calibration for the area as shown in Equation 2 and Equation 3.

$$C = A + (1 - A).B.k \qquad (2)$$

Where:
C = Confidence (%)
A = Percentage of pipe length with complete CCTV, as shown in Equation 3.
B = Calibration Percentage, as shown in Equation 4.
k = low CCTV factor.
If A < 5%, k = 0.5.

If 5%≤A<10%, k = 0.75.
If A≥10%, k = 1.

$$A = \frac{L_{CCTV}}{L} \quad (3)$$

Where:
L = Length of pipe in the study area (m)
L_{CCTV} = Length of pipe in the study area with completed CCTV survey information (m)

$$B = \frac{L_{Match}}{L_{CCTV}} \quad (4)$$

Where:
L_{Match} = Length of pipe in the study area with completed CCTV survey information and a PDA action that matched the CCTV outcome (m)

The results of the citywide analyses were presented as maps. These maps were used to inform the prioritisation of projects and identify areas where further CCTV was required. Figures 3 and 4 are outputs from this analysis.

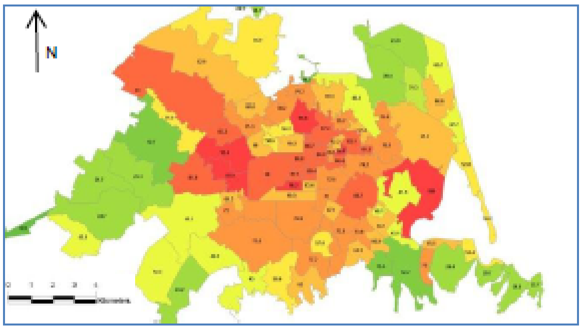

Figure 3: Damage Percentage by Rebuild Area for the Wastewater System

The results for damage percentage are presented as deciles, with red representing high levels of damage (90% to 100%) and dark green representing low levels of damage (0% to 10%)

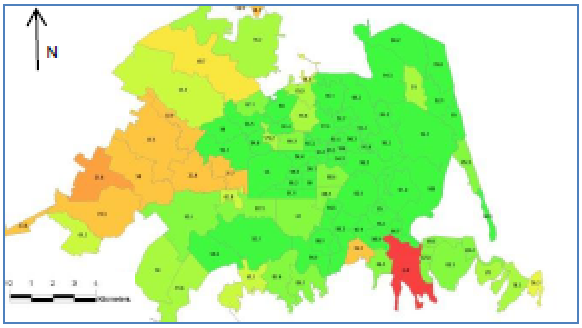

Figure 4: Confidence in the Recommended Actions for Wastewater, by Rebuild Area

The results for confidence are shown as deciles, with dark green represnting high levels of confidence (90% - 100%) and red representing low levels of confidence (0% - 10%)

Scoping and Design

Outputs from the PDA Tool were used to inform the Scoping Team, before Rebuild Areas were handed over to a Design Team for Concept Design and Detailed Design.

The Scoping Team used aggregated information on the breakdown of recommended actions, the source of recommended actions and the summarised characteristics of the Rebuild Area. Outputs were broken down further to give the length of Renewals and number of Repairs by Material, which can affect the methodology, and Diameter, which affects the cost.

Figures 5 and 6 show examples of graphs indicating the breakdown of recommended actions and the source of recommendations respectively.

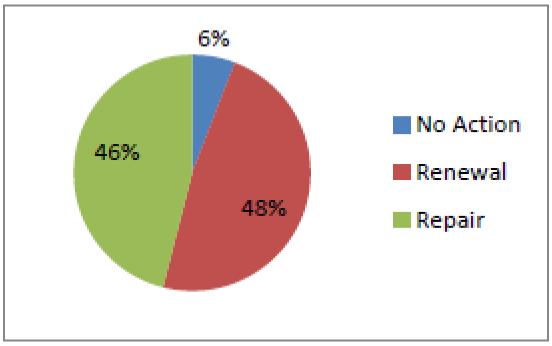

Figure 5: Example of Recommended Actions

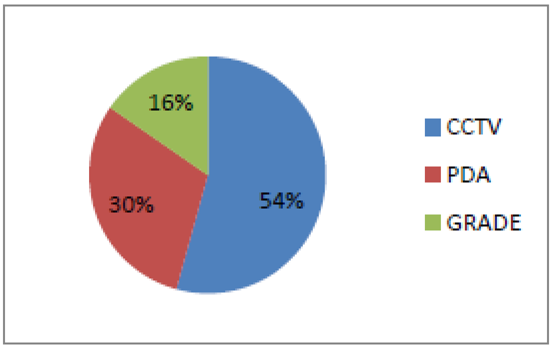

Figure 6: Example of Recommendation Source

Figures 6 and 7 are for an area of Christchurch that has been identified by the Canterbury Earthquake Recovery Authority as unsuitable for rebuilding and the area is to be abandoned. The figures show that the area has extensive damage to the network and that more than half of the network has complete CCTV.

Figures 7 and 8 show the length of pipe in an example area, classified by pipe material, and the split of recommended outcomes by pipe material.

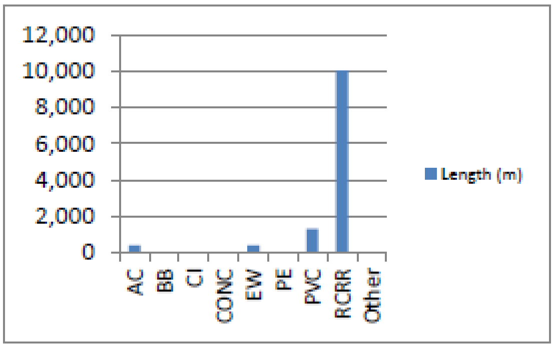

Figure 7: Example of Length of Pipe, Subdivided by Material

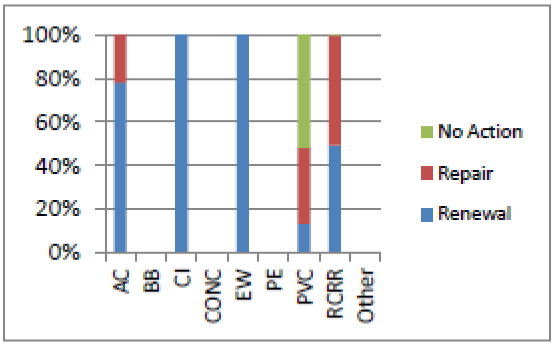

Figure 8: Example of Damage Proportions to Pipes, Subdivided by Material

Figure 7 shows that the majority of the pipes in the example study area are made from reinforced concrete (RCRR). Figure 8 shows that the least damaged material in the example study area is PVC. Note that the amount of Cast Iron (CI) pipes in the example area is too small to be displayed in Figure 7.

Design Teams used the outputs of the PDA Tool at an individual pipe level. CCTV results were always used when they were available. High priority pipes where a CCTV inspection could not be completed due to high water levels, high infiltration rates upstream, blockages and unsafe working conditions for CCTV crews relied on damage predictions from the PDA Tool. Lower priority pipes without CCTV records also relied on PDA Tool outputs when the time and cost implications of obtaining CCTV data could not be justified. An example of a pipe-level map of the PDA outputs is shown in Figure 9.

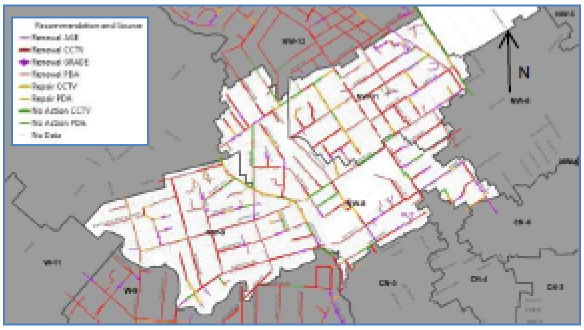

Figure 9: Example of PDA Tool Outputs at an Individual Pipe Level

Asset Assessment

The Asset Assessment Team used outputs from the PDA Tool to scope upcoming CCTV requirements and to identify and prioritise the forward CCTV program. This involved understanding the needs of the users of the CCTV data and agreeing the optimum balance between CCTV observations and PDA predictions.

The Damage and Confidence maps were used together to identify, for example, areas where both damage and confidence were low. These areas were low priority for further CCTV, as the investment in CCTV could exceed the cost of rebuilding the damaged assets. The decision to not undertake further CCTV was always supported by with independent information on network conditions, such as changes to flowrates, operational costs and repair history.

Estimation and Budgeting

Citywide PDA outputs were supplemented with more detailed outputs from individual Rebuild Areas. The PDA Tool was expanded using standard SCIRT unit rates for pipe renewals and pipe repairs to calculate costs at a Rebuild Area level and these were aggregated to provide an independent check of the Estimating Team's work.

<u>RESULTS</u>

The PDA Tool provided information on the recommended action for individual pipes that consistently matched the observed CCTV outcome for between 75% and 95% of the length of the pipes in the area studied. By using combinations of measures the PDA Tool outperformed a single-measure approach, where the CCTV outcome was only accurate for between 45% and 60% of the length of pipes. The outputs could then be processed to inform and support a range of processes undertaken by

SCIRT at a much lower cost than obtaining CCTV data.

CONCLUSION

The PDA Tool was found to be a unique, reliable and accurate method for predicting the condition of earthquake-damaged gravity wastewater and stormwater pipes, and thereby the extent of damage to the network. Ongoing refinement and validation to new CCTV has improved its accuracy and enhanced the understanding of damage to the wastewater and stormwater pipes.

The techniques developed are applicable to the prediction of pipe damage in cities affected by earthquakes in the future.

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Analysis and Design of Manholes in Liquefiable Soils

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Final Year Projects, 2013
Dept. of Civil and Natural Resources Engineering
University of Canterbury
Project supervisor(s): M Cubrinovski and M Hughes

Keywords: *Earthquake, liquefaction, manhole, buoyancy, settlement*

ABSTRACT

This project investigated the effects of liquefaction–induced damage to the Christchurch wastewater manholes, following the February 2011 earthquake as these are key components in the wastewater system. To fully characterise the manhole behaviour, key pieces of information such as manhole geometries, backfill characteristics, embedment depths and water table depths were assigned to Geographic Information System (GIS) datasets, and correlated with liquefaction severity observations and displacements relative to the surrounding ground surface. Highly variable site conditions mean there is high uncertainty around the correlation between liquefaction severity and relative displacements. The parametric analyses also show numerous parameters control manhole uplift. Two of the most important parameters working in tandem to control the uplift are manhole depth and water table depth. Manholes embedded to a depth that exceeds the water table depth are at higher risk of significant displacement than short manholes installed where the water table is shallow. Older cast-in situ square manholes show a generally higher resistance to uplift than more recent circular manholes due to their higher mass. This is observed in correlations between relative displacement and liquefaction severity, and also in parametric analyses.

1. INTRODUCTION

On the 22nd February 2011, Christchurch was struck by a magnitude 6.3 earthquake, causing significant damage to the city's Central Business District (CBD) buildings and the majority of Christchurch's infrastructure. The earthquake induced severe and widespread liquefaction, causing significant damage to approximately 31% of the city's wastewater system (Simpson, Walter, & Gibson, 2013). Due to Christchurch's flat terrain (average slope approximately 0.1-0.2%), the wastewater system is comprised of a low grade gravity network with many pumping stations. The total length of the city network prior to the earthquake sequences was approximately 1800 km, collecting and delivering wastewater to the Bromley treatment plant.

The impact of liquefaction on the gravity pipe network caused significant relative displacement of pipe sections and manholes. This caused a loss in grade of gravity pipes, breakage of pipes and joint damage between pipes and between pipes and manholes. As the wastewater system in Christchurch varies in depth between 2.0 m and 3.5 m, repair requires deep excavations. Of particular interest for this investigation is the relative displacement of manholes and its relation to the liquefaction severity. An earlier report on liquefaction impacts on the Christchurch pipe network concluded that the performance of manholes under seismic loading had not been consistent and required further investigation. However, this report showed a clear relation between liquefaction severity and damage to the potable water and wastewater pipe network (Cubrinovski, et al., 2011). Here, the liquefaction severity maps of Cubrinovski et al. (2011) were used in combination with manhole characteristics and damage observations to identify mechanisms causing relative displacements of manholes. The combined information is presented as a map in Figure 1.

2. CHARACTERISTICS OF THE CHRISTCHURCH WASTEWATER SYSTEM

The minimum diameter of wastewater pipes in Christchurch is 100 mm, used for private connections. However the vast majority of the city has been developed using 150–225 mm pipes. Pipes of > 300 mm diameter make up the arterial collection system, transporting waste to Bromley. Wastewater pipes are laid in the centre of the road with the majority of pipes at a depth of between 2.0 m and 3.5 m. The spacing of manholes in the city is between 100 m (for 150–225 mm diameters) and 180 m (for pipe diameters greater than 1600mm).

There have been many different construction methods and geometries of manholes used in the construction of Christchurch's wastewater system. In addition to these, methods of connecting manholes to the system and backfill materials have also changed, resulting in much variability in system design across the city.

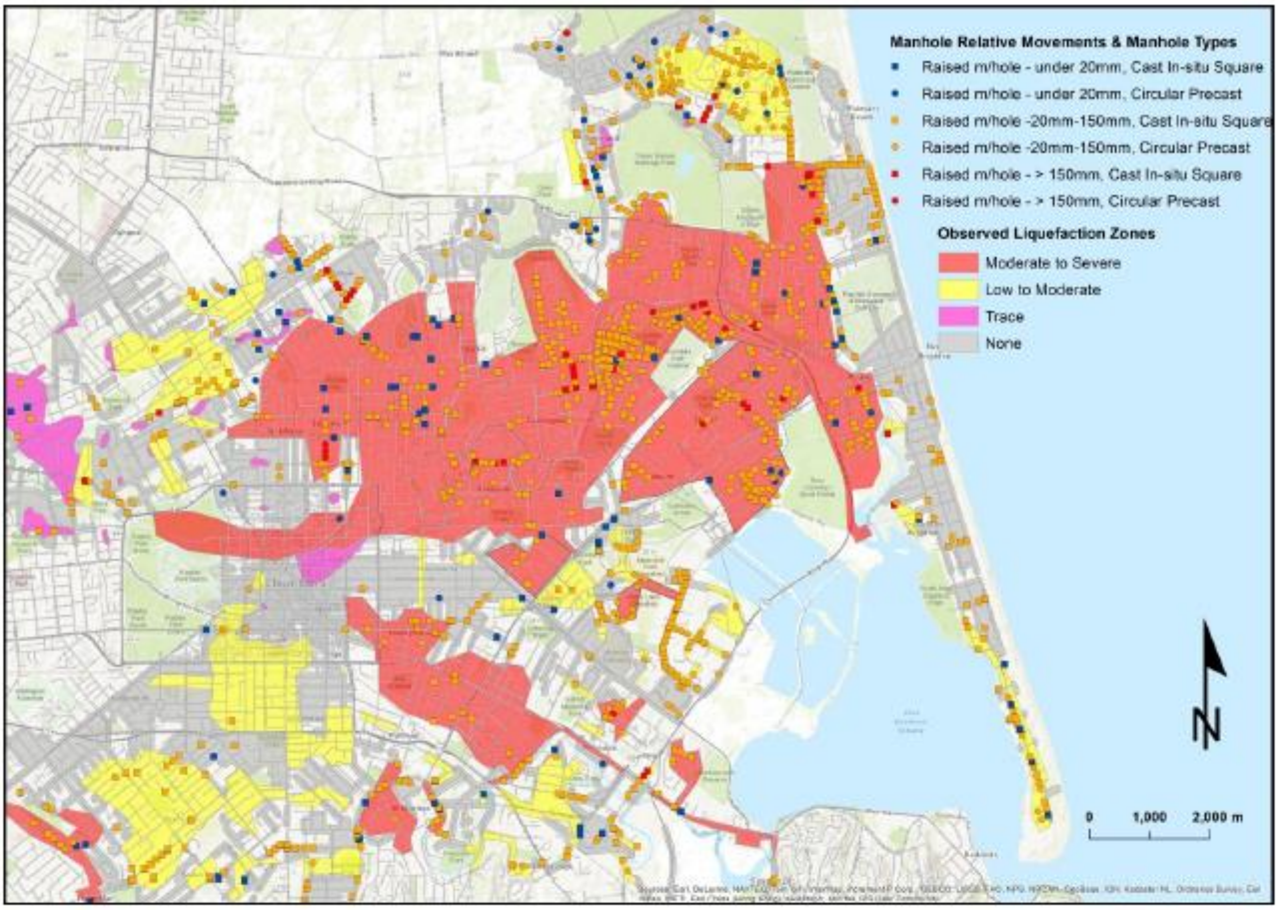


Figure 1: Map of Christchurch showing liquefaction severity, manhole location and relative displacements. Modified from (Cubrinovski & Taylor, 2011) **and** (McNeill & English, 2011).

2.1. Manholes

Early manholes constructed before 1925 using bricks, are prominent in the central city within an approximate area of 1550 ha centred on the CBD (Wilson, 1989). These had an upside down pear shape to increase flow in the base of the manhole. They were constructed from brick and mortar on site by hand within the excavated ground. No specifications or specific documentation on the method of construction are available; it is believed the quality of construction relied on the experience and ability of contractors. The lack of specifications for these manholes is not a significant issue for our investigation due to their relatively low numbers.

The transition from brick to unreinforced cast in-situ square manholes is believed to have occurred during a pause in pipe laying between 1912 and 1926. Cast In-situ square manholes are the most predominant structural type in the city, with specifications presented in Figure 2. These specifications are still in current use (Christchurch City Council, 2013). The inclusion of steel reinforcing is believed to have occurred in the 1970s with the development of precast circular manholes. Steel reinforcement has a negligible effect on the weight of manholes, and as the structural integrity of the manholes is not under investigation the effects of steel reinforcement are discounted.

From approximately 1970 circular precast manholes were installed throughout the city's wastewater network for pipes with a diameter < 400 mm. These were predominantly 1050 mm in diameter circular manholes with steel reinforcement, as shown in Figure 2. Circular manholes are prominent structures in the wastewater system due to a large proportion of the network having a diameter < 400 mm.

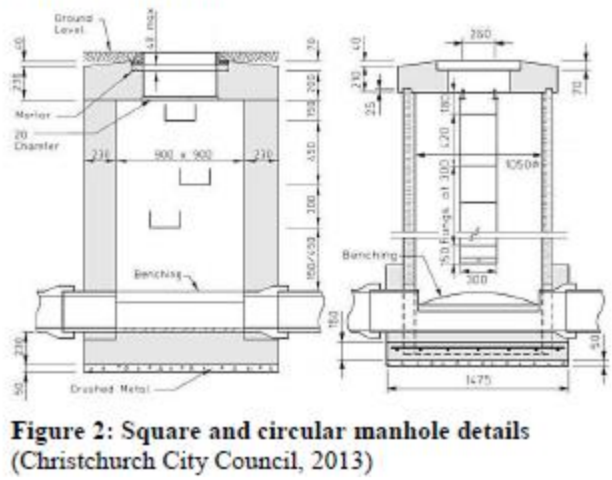


Figure 2: Square and circular manhole details (Christchurch City Council, 2013)

The production of square precast manholes began in 1980 for use on pipes of diameter > 450mm. These and special cast in-situ square manholes have been used for large pipe diameters and those with irregular geometry. Their specifications were deemed irrelevant to this investigation due to their low numbers.

The year of manhole installation and the maximum diameter of wastewater pipe entering the structure are presented in Table 1.

Table 1: Manhole type characterisations

Year of Installation	Pipe Diameter Limit	Manhole Type
Before 1925	Any	Brick Construction
1926 - 1969	Any	Cast In-situ Sq
1970 - 1979	>400mm	Cast In-situ Sq
	<400mm	Circular Precast
	>750mm or special configuration	Special Cast In-situ Square
1980 - present	>400mm & <750mm	Square Precast
	<400mm	Circular Precast
	>750mm or special configuration	Special Cast In-situ Square

The mass of each manhole type was determined using volumetric specifications from Christchurch City Council (2013) (Figure 2) and a concrete unit weight assumed to be 24 kNm^{-3} based on engineering knowledge. Table 2 presents the mass of the components for the manholes in the analysis.

Table 2: Masses of manhole types studied

Component	Square (900 x 900 mm)	Circular (1050 mm dia.)
Mass of top (t)	1.101	0.596
Mass of base (t)	1.041	0.627
Mass of shaft ($t\ m^{-1}$)	2.543	0.548

2.2. Backfill

The backfill material used throughout the city has changed significantly throughout the construction of the network. Characterisation of the backfill (including grain size distribution, density and permeability of soils) and construction methods is difficult due to the variation in engineering practice and specifications (or lack of records) over time, and variation in native soil make-up across the city. From 1880 through to the mid-1940s excavated native soils were used in the backfilling of trenches for pipes and manholes for trenches within an approximate area of 5200 ha (centred on the city centre) (Wilson, 1989). This can be assumed to be a mixture of loams, clay and peat soils.

Backfills in the eastern suburbs are predominantly excavated sand (Walter, 2013). This is the typical backfill type in the eastern suburbs including North Brighton, Aranui, Parklands and South Brighton. From 1945 through to the mid-1960s there is evidence of both excavated material and the beginnings of specifically graded imported backfill that became standard for Christchurch Drainage Board (CDB) projects. The following specification as described by Buzz March of March Construction was the standard till the early 1990s:

- Base of AP20/AP40 around pipe (up to 150 mm above the pipe if plastic)
- River run aggregate to 150 mm from surface
- AP40 to level allowing surfacing

Specifications set out in the Christchurch City Council (CCC) Construction Standard Specification (CSS) Part 1- General (Christchurch City Council, 2013), currently specify the backfill characteristics and construction standards for trenches throughout the city. Excavated backfill is still used when approved by the contract engineer, however the current backfill specification includes:

- AP20/AP40 used as haunching, with geotextile if necessary. This varies depending on pipe diameter and material
- CCC pitrun and CCC AP65 compacted to a minimum dry density of 2,150 kgm^{-3}, with surfacing applied within 5 days

Characterisation of backfill is difficult due to variations in materials and construction methods. The compaction of trenches has varied extensively. Specifications to test compaction have only been a requirement since the mid-1990s (March, 2013). Prior to this, it was at the contractor's discretion how to achieve an adequate compaction with work overseen by a Clerk of Works (representative engineer from CDB) and the backfill inspected for settlement over the maintenance period. Therefore detailed characterisation is limited.

From extensive discussions and information gathered regarding backfill characteristics, general backfill types for the city were determined. These are summarised in Table 3.

Table 3: Backfill type characterisations

Year	Location	Backfill Type
1880 - 1945	City Wide	Locally Excavated Soils
1940 - 1960	Eastern Suburbs	Locally Excavated Sand
1946 - 1959	Central & Western Suburbs	Likely Locally Excavated Soils
1960 - 1990	City Wide	CDB Spec (AP20/AP40 haunching, river run aggregate to 150mm to surface and AP40 to surfacing level)
1990 - present	City Wide	CCC CSS Spec (AP20/AP40 haunching, geotextile, CCC pitrun and/or CCC AP65)

3. METHODOLOGY

3.1. Background Information

Core GIS Data

A GIS database (courtesy of the Stronger Christchurch Infrastructure Rebuild Team (SCIRT)) of the Christchurch wastewater system includes the spatial distribution and associated attribute information of waste water pipes, manholes, and pump stations. This was used to identify the manholes currently in service on the network and their locations throughout the city. There are approximately 29,000 manholes installed throughout the city.

Liquefaction Severity Map

The investigation made use of a liquefaction map of observed liquefaction severity from a drive through reconnaissance in the days following the 22nd February 2011 earthquake, compiled by University of Canterbury (UC) staff (Cubrinovski & Taylor, 2011). The liquefaction map shown in the background of Figure 1 indicates the following zones/areas:

(a) moderate to severe liquefaction (with very large areas covered by sand ejecta, mud and water, large distortion of ground and pavement surfaces, large fissures in the ground, and significant liquefaction-induced impacts on buildings and infrastructure), (b) low to moderate liquefaction (with generally similar features as for the severe liquefaction, but of lesser intensity and extent), (c) liquefaction predominantly on roads with some on properties (where heavy effects of liquefaction were seen predominantly on roads, with large sinkholes and 'vents' for pore pressure dissipation, and limited damage to properties/houses), and (d) traces of liquefaction (with clear signs of liquefaction, but limited in extent and deemed not damaging for structures) (Cubrinovski, et al., 2011).

Relative Displacements

The GIS dataset of selected manholes' relative displacements originated from a detailed drive-through reconnaissance by CCC staff. Reconnaissance was conducted as a means of assessing urban road damage for cost analysis following the February earthquake (McNeill & English, 2011). Only 8.8% of manholes have a recorded relative displacement as the primary focus of the evaluation was road damage, not manhole movement observation. The relative displacements of the manholes were placed by CCC into three categories: < 20mm, 20-150mm and > 150mm. Note that this is movement of the manhole relative to the surrounding ground surface and could include flotation of the manhole, settlement of the ground surface, or a combination of both.

3.2. Characterisation of Manholes and Associated Backfill

Due to the limited information in the original wastewater network database, key pieces of information regarding manhole characteristics had to be deduced via data overlaying, researching historical specifications and making assumptions. There is a degree of uncertainty in these assumptions, due to technologies for manhole construction evolving over time and the 'phasing in' of updated manhole and backfill construction methodologies. Investigation of historical manhole specifications was undertaken through extensive discussions with SCIRT and CCC engineers, as described earlier.

The GIS investigation undertaken is described in Figure 3, highlighting key steps, processes, inputs and outputs. Unnecessary and out-dated information was edited from the two GIS data sets shown as the initial steps in Figure 3. The depth of the manholes was then approximated by assigning the depth of the deepest pipe entering the manhole, with the addition of specific manhole base thickness (300 mm for square manholes and 200 mm for circular). There is uncertainty in this method due to the inability to determine where the pipes were measured from as only one depth value is given per pipe section in the CCC GIS dataset.

Using the year of manhole installation, maximum pipe diameter entering the manhole and historical specifications, the manholes were assigned to a specific type, as presented in Table 1. The relative displacements observed by CCC staff and the liquefaction-induced damage dataset were assigned to the updated city-wide manhole characterisations. The dataset of manhole relative displacements (constructed using GPS locations by CCC engineers) was spatially offset from the core manhole dataset.

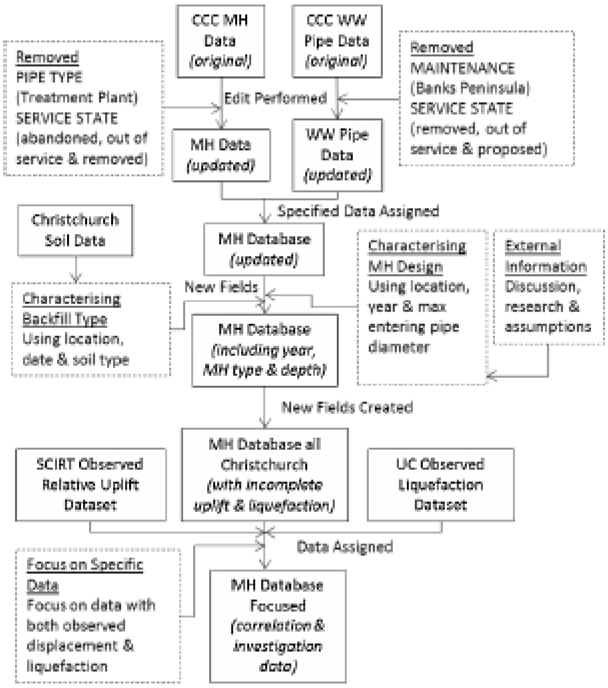


Figure 3: Flow chart of characterisation process in GIS

To assign displacements to the core dataset, a buffer region was applied to identify the nearest matching manhole displacement value. Where buffer analysis was insufficient to assign displacements, judgement was used. This process was also undertaken for the observed liquefaction data with the exception of trace liquefaction that could not be assigned to any manholes under investigation. The resulting manholes with both observed relative displacements and observed liquefaction severity were used in this analysis and are presented in Figure 1.

4. RESULTS AND CORRELATIONS

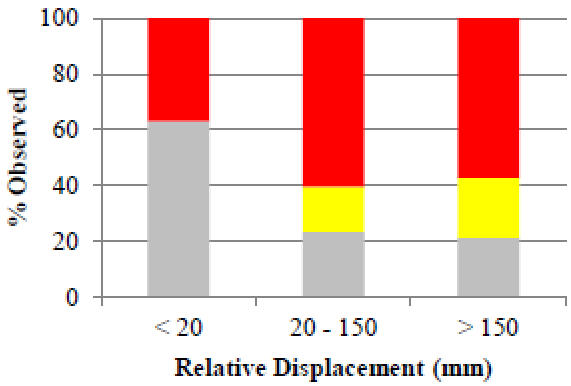
The two types of manholes of largest proportion in the Christchurch City wastewater system are square concrete cast in-situ manholes and circular precast manholes. Investigations were focussed on manholes with these geometries that also had specification, liquefaction severity and relative displacement information associated with them in the final GIS dataset. Correlations between the geometric details (e.g. shape and mass), the relative displacements and the observed liquefaction severity were investigated.

It should be noted that the number of manholes with sufficient information is much less than the total number of manholes currently in the city. This is unfortunate, but typical of inspections in the field where there are a very large number of structures to be inspected. This is compounded by the fact that two different groups undertook the inspections for the liquefaction severity and the relative displacements, meaning the areas covered were different. To complicate matters further, the number of circular manholes with adequate information is much less than the number of square manholes. This is due to the spread of the manholes over the city; square manholes are older and hence closer to the city centre and in areas developed earlier in the city's history. Circular manholes are limited to newer areas or at locations where replacement has been carried out. In some instances, the number of circular manholes available for correlation is very small (e.g. only three manholes with greater than 150 mm relative displacements in areas of no liquefaction were observed). With this in mind, the comparison of performance between circular and square manholes based on percentages of manholes is perhaps biased and not representative of the total quantity of manholes in the city.

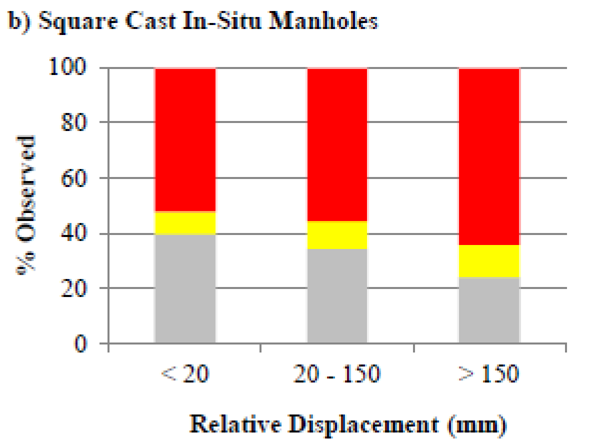
Figure 4 a) shows the percentages of each relative displacement category due to liquefaction severity for circular manholes, and Figure 4 b) shows the percentages of manholes in each relative displacement category due to liquefaction severity for square manholes. For the circular manholes with low relative displacement (< 20 mm), 63% were in areas of no liquefaction, and 37% of the manholes with the same low relative displacements were in areas of moderate to severe liquefaction (Figure 4 a)). The result that a higher percentage of manholes exhibiting low relative displacements were in areas of no liquefaction is expected. At the other extreme of the relative displacement scale, the highest percentage (57%) of manholes exhibiting high relative displacements (> 150 mm) were in areas of moderate to severe liquefaction. This is also expected, as severe liquefaction is expected to be more damaging to structures in and above the ground. 21% of the manholes with the same high relative displacements were in areas of no liquefaction.

	Liquefaction Severity
(red)	Moderate – Severe Liquefaction
(yellow)	Low – Moderate Liquefaction
(grey)	No Liquefaction

a) Circular Pre-Cast Manholes



Relative Displacement	Total Number of Manholes
< 20 mm	46
20 – 150 mm	343
> 150 mm	14



Relative Displacement	Total Number of Manholes
< 20 mm	96
20 – 150 mm	764
> 150 mm	50

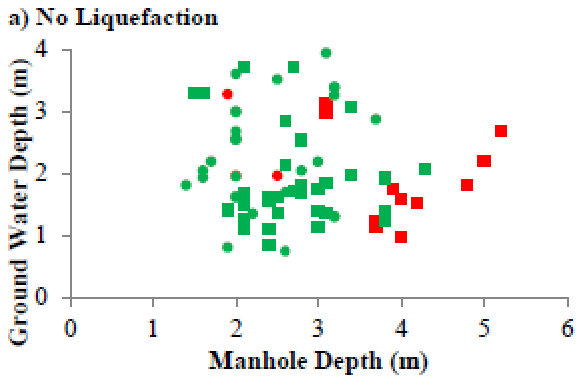
Figure 4 a) and b): Relationship between relative displacement and liquefaction severity for a) circular manholes and b) square manholes

For the square manholes with low relative displacement, 40% were in areas of no liquefaction, and 52% of the manholes with the same low relative displacements were in areas of moderate to severe liquefaction (Figure 4 b)). The result that a lower percentage of manholes exhibiting low relative displacements were in areas of no liquefaction is not expected. The highest percentage (64%) of square manholes exhibiting high relative displacements was in areas of moderate to severe liquefaction. This is expected, as severe liquefaction is expected to be more damaging to structures in and above the ground. 24% of the manholes with the same high relative displacements were in areas of no liquefaction.

Groundwater depth information was obtained from Canterbury Geotechnical Database (2013) for the purposes of further explaining these trends. Figure 5 a) and b) show plots of groundwater depths against manhole depths for areas of no liquefaction and moderate to severe liquefaction respectively for square and circular manholes. For a constant ground water depth, an increasing manhole depth increases the relative displacement (Figure 5 a) and b)). There is clear indication that large relative displacement of manholes occurred for manhole depths > 3.0 m in areas of moderate to severe liquefaction. This is due to the excess pore water pressure acting on the base of the manhole being higher at greater depths below the water table. Both the water table depth and the manhole depth are key parameters controlling uplift of buoyant structures, and are two parameters investigated in the next section on parametric analyses.

From the information presented in Figure 5, the reason for the reasonably high percentage (37%) of circular manholes with low relative displacement in areas of moderate to severe liquefaction is the presence of a high water table (causing high severity of liquefaction) in combination with relatively shallow manhole embedment depths (Figure 4 a)). The shallow embedment depth limits the build-up of excess pore-water pressure acting on the base of the manhole. Circular manholes having high relative displacements while being in areas of no liquefaction (Figure 4 a)), is due to the embedment depth of the manhole being large, combined with a deep water table. A deep water table causes a thick, non-liquefiable crust that prevents (or limits the extent of) liquefaction establishing on the ground surface. The reason for 52% of square manholes showing low relative displacement in areas of moderate to severe liquefaction is due to a greater number of manholes being embedded at shallow depths (Figure 4 b)). Similar to the circular manholes, the 24% of square manholes with large relative displacements in areas of no liquefaction is due to the embedment depth of the manhole being large, combined with a deep water table. However, square manholes performed marginally better based on the higher percentage of manholes that exhibited low relative displacements situated in areas of moderate to severe liquefaction.

■	Square (> 150 mm relative displacement)
●	Circular (> 150 mm relative displacement)
■	Square (< 20 mm relative displacement)
●	Circular (< 20 mm relative displacement)



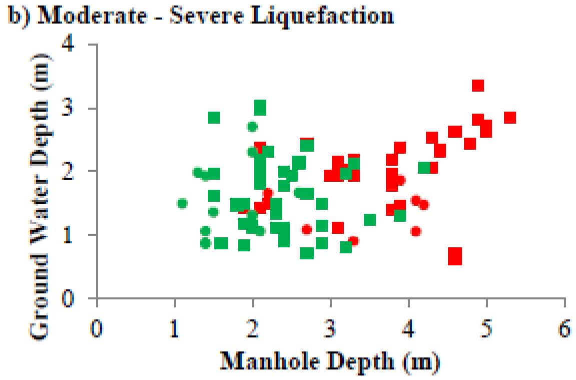


Figure 5 a) and b): Plot of groundwater depth against manhole depth for areas of a) No liquefaction; and b) Moderate to severe liquefaction (both manhole types)

The reason for low relative displacements of square manholes is due to the heavier mass of the square manhole. Hence, square manholes are expected to uplift less in areas where moderate to severe liquefaction is prevalent. It should be noted that these conclusions have been made based on the limited sample size available, and significant uncertainty exists due to the highly variable ground conditions and spread of the different manhole shapes in the city.

5. PARAMETRIC ANALYSIS

To achieve an analysis as representative as possible for the conditions in Christchurch at the time of the February 2011 earthquake, CPT, ground motion data and ground water levels were obtained for three areas of interest and where an overall completeness of data was available (Parklands, Avonside and Aranui). Ground water level data in Christchurch, modelled from measurements taken from specific sites throughout the city, was assigned to the characterised manholes, along with the peak ground accelerations (Canterbury Geotechnical Database, 2013).

Simplified calculations of uplifts due to liquefaction based on the method of Sasaki and Tamura (2004) for circular and square manholes were carried out for varying depths of manholes, varying depths of water table, varying depths of liquefiable layers and varying penetration resistances. For simplicity, the peak ground accelerations were averaged for the three areas chosen. Figure 6 a) to 8d) show the results of the uplift analyses to give the uplift envelopes shown for a time (after liquefaction starts) of 30 seconds. This time was chosen as it is comparable to the time used in Sasaki and Tamura (2004) and based on engineering judgement. Square manholes, due to their heavier mass, are expected to exhibit smaller uplift than the lighter, circular manholes. There is a clear and steep increase in uplift for values of q_c less than 5 MPa, indicating this is one of the key parameters controlling uplift. Uplifts are small for $q_c > 5$ MPa; a higher value of q_c indicates the soil has a higher density and an increased resistance to liquefaction. The depth of the water table below the ground surface is also a key parameter controlling the uplift of manholes, when analysed together with manhole depth. When the manhole depth is held constant, shallow water table depths (0.5 m) caused greater uplifts compared to depths of about 1.5 m, due to a larger portion of the soil (in which the manhole is embedded) liquefying. Similarly, holding the water table depth constant but increasing the depth of the manhole results in higher calculated uplifts. For manhole depths of 3.5 m the uplifts are 4-6 times greater than manhole depths of 1.5 m. The observation that manhole depth and water table depth are key controlling parameters is consistent with the results of the correlations in the previous section. The thickness of the liquefied layer beneath the manhole controls the amount of excess pore water pressure that can build up; a thicker layer causes higher pressures.

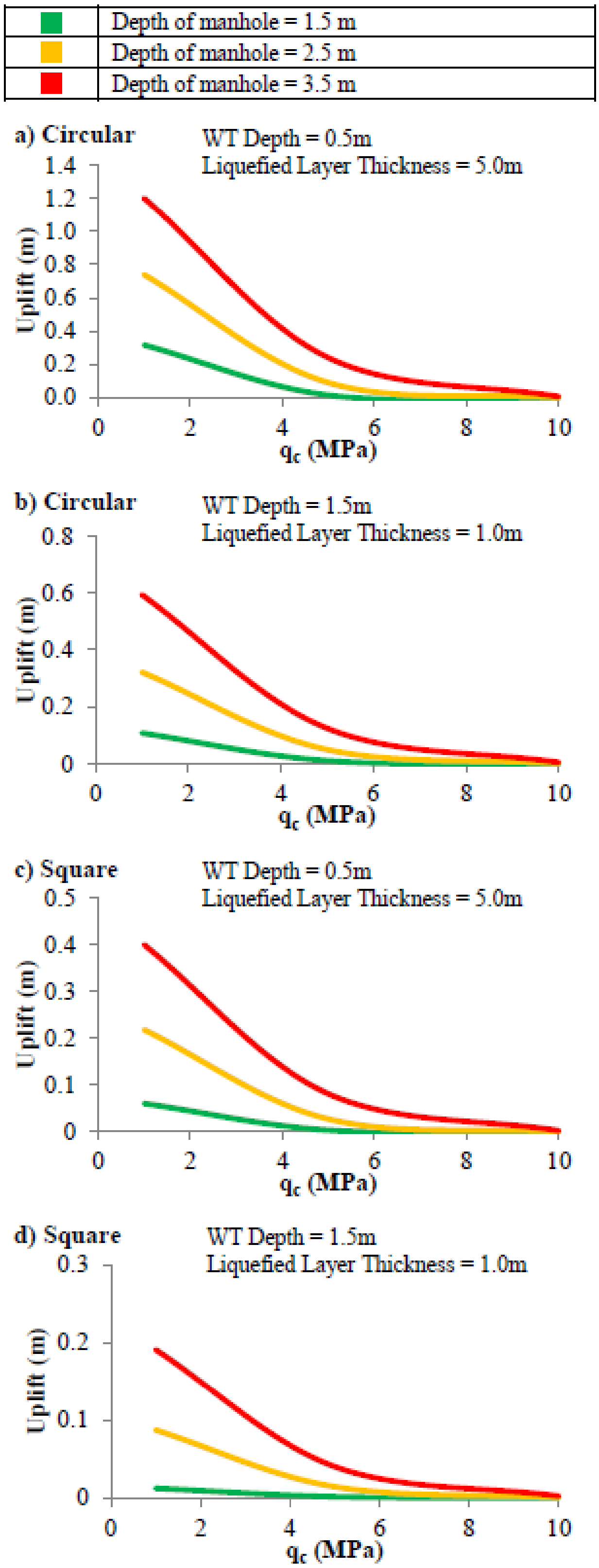


Figure 6 a) to d): Calculated uplifts for varying CPT Resistance, q_c, for a) and b) circular manholes; c) and d) square manholes

6. CONCLUSIONS AND RECOMMENDATIONS

This paper has shown that the behaviour of manholes in liquefiable soils is highly variable and there are many factors that control the magnitudes of relative displacements. Some key conclusions are:

- The vulnerability of the system is highly variable due to the development of technologies and construction methods over time. Liquefaction severity is also highly variable over large areas.
- Two dominant manhole types (square cast in-situ and circular pre-cast) were the focus of the investigation. The key difference between these two types is the weight (square manholes being approximately 3 times heavier than circular manholes) which was shown in parametric analyses to be an important parameter controlling uplift.
- Manholes assigned with relative displacement and observed liquefaction severity data were analysed. A clear link between liquefaction severity and observed relative displacements was found, with manholes showing less relative displacement in areas of no liquefaction (up to 63%) and more in areas of high liquefaction severity (up to 57%), as expected.
- The depth of manhole embedment was a key parameter controlling the observed relative displacements. There was a clear transition between relative displacement severities at approximately 3.0 m embedment depth. Shallow manholes performed better with less relative displacements observed. Very deep manholes had high levels of observed relative displacement. Parametric analyses confirmed these observations.
- The parametric analyses demonstrated that many parameters control the rate and maximum uplift of manholes. As discussed, the embedment depth and the water table depth are two of these key parameters. CPT resistance and liquefied layer thickness are also significant parameters. Uplift increases significantly for CPT resistance less than 5 MPa.

It became clear during the project that future investigations regarding the performance of infrastructure in seismic events would be made significantly easier if the database was kept up to date with vital information such as what was outlined in the body of this report. Progressive confirmation of the characterisations made in this report should also be carried out.

7. ACKNOWLEDGMENTS

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